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NORTHROP TECHNICAL REPORT

COMPRESSION PROPERTIES OF POROUS LAMINATES IN THE PRESENCE OF PLY DROP-OFFS AND FASTENER HOLES

CONTRACT N00019-82-C-0156
CONTRACT N00019-82-C-0063

FINAL TECHNICAL REPORT

R. L. Ramkumar
D. F. Adams

March 1984

Prepared for:

DEPARTMENT OF THE NAVY
NAVAL AIR SYSTEMS COMMAND
WASHINGTON, D.C. 20361

by

Northrop Corporation
Aircraft Division
One Northrop Avenue
Hawthorne, California 90250

and

University of Wyoming
Composite Materials Research Group
Mechanical Engineering Department
Laramie, Wyoming 82071

NORTHROP TECHNICAL REPORT

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
Compression Properties of Porous Laminates in the Presence of Ply Drop-Offs and Fastener Holes

5. TYPE OF REPORT & PERIOD COVERED
Final Technical Report
June 1982 - June 1984

6. PERFORMING ORG. REPORT NUMBER
NOR 84-1

7. AUTHOR(s)
R. L. Ramkumar
D. F. Adams

8. CONTRACT OR GRANT NUMBER(s)
N00019-82-C-0063
N00019-82-C-0156

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Northrop Corporation
Aircraft Division
One Northrop Avenue
Hawthorne, CA 90250

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
Department of the Navy
Naval Air Systems Command (AIR5304-C)
Washington, D.C. 20361

12. REPORT DATE
March 1984

13. NUMBER OF PAGES
91

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

AS1/3501-6 graphite/epoxy; porosity; ply drop-off; fastener holes; static compression tests; constant amplitude fatigue; environmental effects; non-destructive evaluation; photomicrographs.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An experimental program was conducted to quantify the effects of porosity, ply drop-offs and fastener holes on the compression response of AS1/3501-6 graphite/epoxy laminates. Static tests yielded ultimate compressive strains (ε^{cu}), and constant amplitude fatigue tests yielded threshold strain levels (ε^{th}) below which fatigue failures will not occur in the specimens for at least a million cycles at R=10 and ω=10 Hertz. Results from earlier studies on the

20. Abstract

same material quantified the effects of compressive loading on plain specimens, specimens with ply discontinuities (drop-offs), and specimens with a near uniform porosity distribution. In the reported study, the interaction among the various stress raisers -- ply drop-offs, porosity and fastener holes -- was studied.

Test environment affected the ε^{cu} values significantly. ε^{cu} decreased as the environment changed from -65^0F wet to room temperature dry, room temperature wet, 218^0F dry and 218^0F wet conditions, in the specified order. Porosity, approximately 2.5 to 4.5% by volume, caused significant ε^{cu} reductions that were dependent on the laminate configuration. The largest reduction was realized in $[0]_{nt}$ specimens. In specimens with a $[0_{16}/\pm45_5/90_4]_c$ to $[0_{14}/\pm45_5/90_4]_c$ configuration change at midlength, achieved by dropping two 0^0 plies there, porosity introduced a slight reduction in ε^{cu} over that caused by ply discontinuities. When a 3/16 in. diameter hole was drilled at the ply drop-off location, the effect of porosity on ε^{cu} was minimal. Also, the transfer of 10% of the total load as a fastener bearing load at the ply drop-off location did not affect ε^{cu} significantly.

PREFACE

This report was prepared by Northrop Corporation under Contract N00019-82-C-0156 and includes an input from the University of Wyoming under Contract N00019-82-C-0063. The contracts were administered by the Naval Air Systems Command, and were monitored by Mr. M. Stander until November 1983 and by Mrs. F. Lukeman thereafter. The key program personnel and their responsibilities are listed below:

R. L. Ramkumar	Program Manager and Principal Investigator for Contract N00019-82-C-0156
D. F. Adams	Program Manager and Principal Investigator for Contract N00019-82-C-0063
A. Hall	Test panel fabrication
B. J. Mays	Specimen preparation
R. T. Kessler	Photomicrographs, Image Analysis
T. R. Miller	Specimen testing

The authors thank Ms. B. Parish for typing the manuscript and Ms. R. Cordero for her assistance with illustrations.

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SECTION 1

INTRODUCTION AND SUMMARY

1.1 Introduction

The establishment of acceptance/rejection criteria for laminated aircraft structural components requires the development of a quantitative relationship between routine fabrication quality control measurements and the corresponding mechanical properties of the laminate. This task becomes difficult when defects and discontinuities are simultaneously present at any location in the structural component. Discontinuities in the form of ply drop-offs and cut-outs, and manufacturing defects like porosity, are commonplace in laminated structures. In laminated skins, a thickness change is normally introduced by removing selected layers of the material at specified locations, resulting in stress concentration at the ply drop-off locations. When skins are attached to spars or ribs through fasteners at these ply drop-off locations, an additional stress concentration is introduced at the fastener locations. Porosity is the most common material-related or process-induced manfacturing defect. While it is detected easily, using non-destructive inspection procedures, its severity is difficult to quantify. The presence of porosity at a discontinuity location in a laminated component will impact the acceptability of the component and is the subject of this report.

This is the last in a series of studies that investigates the effects of defects and discontinuities on the compression properties of AS/3501-6 graphite/epoxy laminates (References 1-3). The baseline properties of unflawed laminates are used to quantify the individual and combined effects of selected defects and discontinuities. Porosity--more severe than what is normally detected in production components, ply drop-offs and fastener locations have been selected to be the defects and discontinuities of interest. Most of the baseline test results were generated in Reference 1. The effect of discontinuities was studied in Reference 2, and the effect of uniform porosity on the compression properties was studied in Reference 3.

In this study, the combined effect of porosity and discontinuities (ply drop-offs and fastener holes) is investigated.

1.2 Summary

A summary of test results from References 1 to 3, and from the reported program, is presented in Figures 1 to 4 and Tables 1 to 4. Figure 1 and Table 1 summarize the test results on $[0]_{24T}$ AS/3501-6 specimens. Tests were conducted on porous and nonporous specimens under various environmental conditions. Ultimate compressive strain values were obtained from static tests, and the threshold cyclic strain amplitude, below which specimens will not fail for at least 1.25 x 10^6 cycles of constant amplitude fatigue loading at R=10 and ω=10 Hertz, were also obtained. R is the algebraic minimum-to-maximum cyclic load ratio, and ω is the test frequency. Figure 2 and Table 2 summarize similar test results on $[90]_{24T}$ specimens, and Figure 3 and Table 3 present the summary for $[\pm 45]_{6s}$ specimens. Table 4 lists the data for $[0_{16}/\pm 45_5/90_4]_c$ AS/3501-6 specimens, and Figure 4 presents these results in a bar chart format.

It is seen from Figures 1 to 4 that test environment affects the ultimate compressive strain (ε^{cu}) values significantly. RTD denotes room temperature, dry conditions; RTW denotes room temperature, wet (saturation level moisture content at 95% relative humidity) conditions; -65FW denotes -65°F, wet conditions; 218FD denotes 218°F, dry conditions; and 218FW denotes 218°F, wet conditions. The largest ε^{cu} is realized under -65FW conditions and the smallest ε^{cu} is measured under 218FW conditions. RTD, RTW and 218FD values lie between -65FW and 218FW values in decreasing order.

Porosity, approximately 2.5 to 4.5% by volume, and uniformly distributed through the thickness of the specimen, reduces ε^{cu} values to different extents that are dependent on the laminate layup. The largest reduction is realized in $[0]_{24T}$ specimens. Test environment influences the ε^{cu} values of porous specimens in a manner similar to that observed in nonporous specimens.

The effect of two types of ply drop-offs on the ε^{cu} values for $[0_{16}/\pm 45_5/90_4]_c$ specimens, under various environmental conditions, is compared in Figure 4. The strain concentration due to the ply drop-offs is increased

TABLE 1. SUMMARY OF COMPRESSION DATA ON $[0]_{24T}$ SPECIMENS.

Specimen Type	Environment	ε^{cu} (μin/in)	ε^{th*} (R=10, ω=10 Hz.)
Plain, Nonporous	RTD	-15,100	-7,040
	RTW	-13,300	---
	218FD	-11,000	---
	218FW	-11,900	---
Plain, Porous	RTD	- 7,774	
	RTW	- 6,098	-4,500

* Maximum cyclic compressive strain below which no fatigue failure occurs for at least 1.25×10^6 cycles at R=10 and ω=10 Hz.

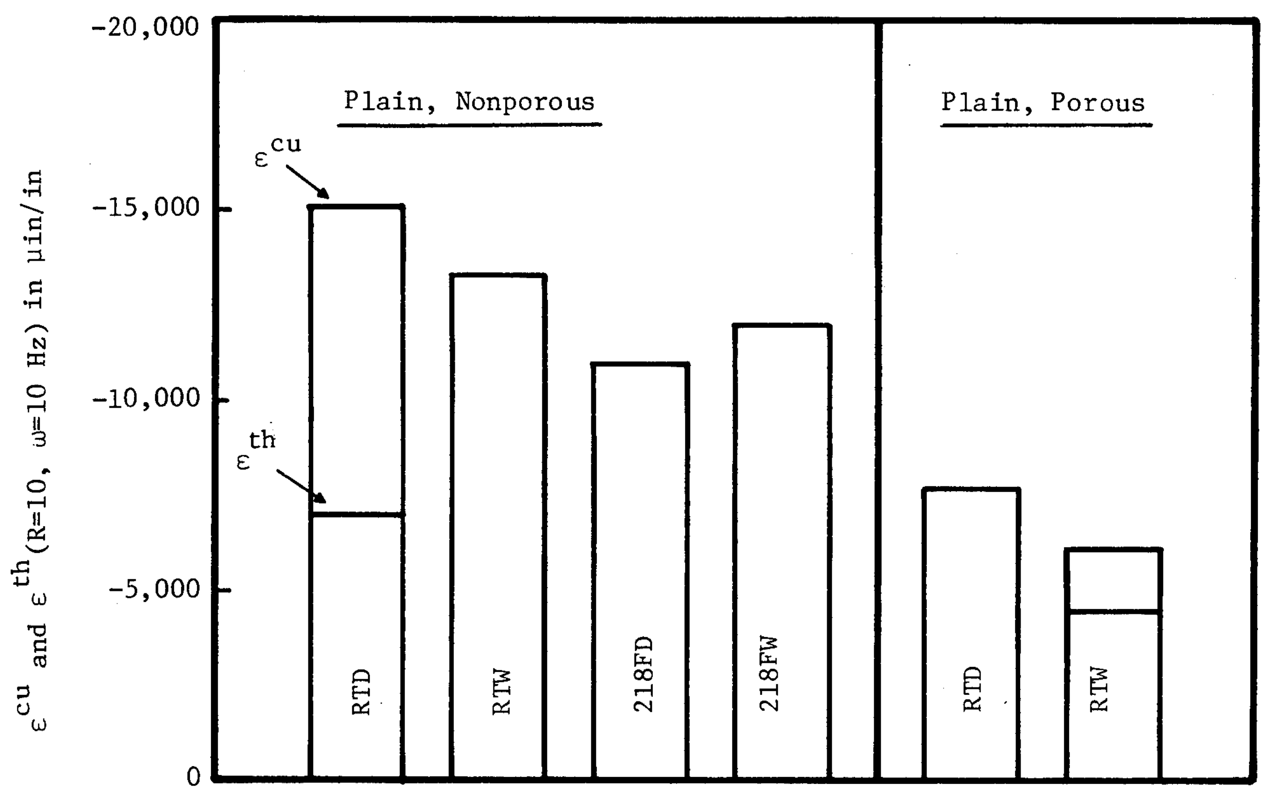


Figure 1. Compression Data on $[0]_{24T}$ Specimens.

TABLE 2. SUMMARY OF COMPRESSION DATA ON $[90]_{24T}$ SPECIMENS

Specimen Type	Environment	ε^{cu} (μin/in)	ε^{th*} (R=10, ω=10Hz)
Plain, Nonporous	RTD	-30,300	-13,500
	RTW	-30,600	---
	218FD	-25,800	---
	218FW	-14,100	---
Plain, Porous	RTD	-19,586	---
	RTW	-17,738	- 9,600

* Maximum cyclic compressive strain below which no fatigue failure occurs for at least 1.25×10^6 cycles at R=10 and ω=10 Hz.

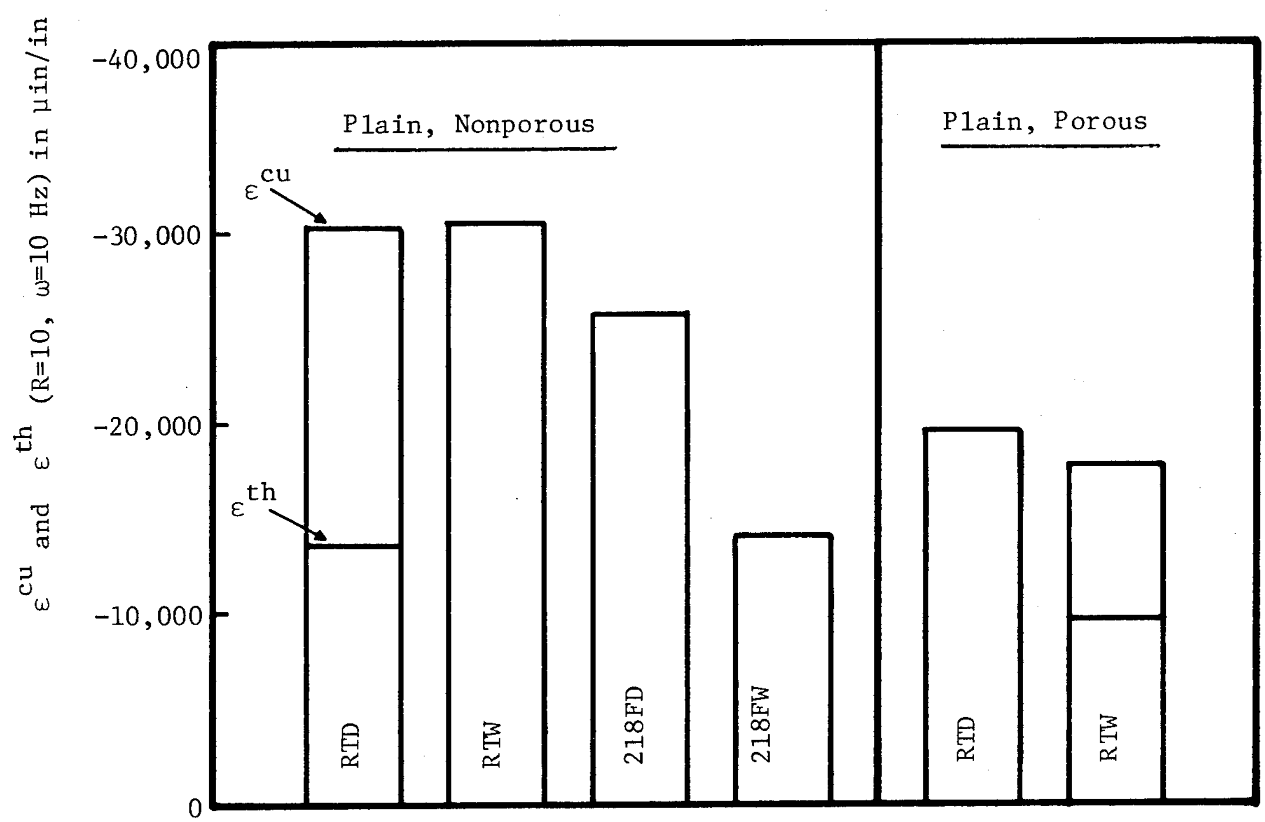


Figure 2. Compression Data on $[90]_{24T}$ Specimens.

TABLE 3. SUMMARY OF COMPRESSION DATA ON $[\pm 45]_{6S}$ SPECIMENS.

Specimen Type	Environment	ε^{cu} (μin/in)	ε^{th}* (R=10, ω=10 Hz)
Plain, Nonporous	RTD	-30,700	-10,500
	RTW	-27,900	-10,500
	218FD	-22,000	---
	218FW	-32,000	---
Plain, Porous	RTD	-23,830	---
	RTW	-19,325	-10,000

* Maximum cyclic compression strain below which no fatigue failure occurs for at least 1.25×10^6 cycles at R=10 and ω=10 Hz.

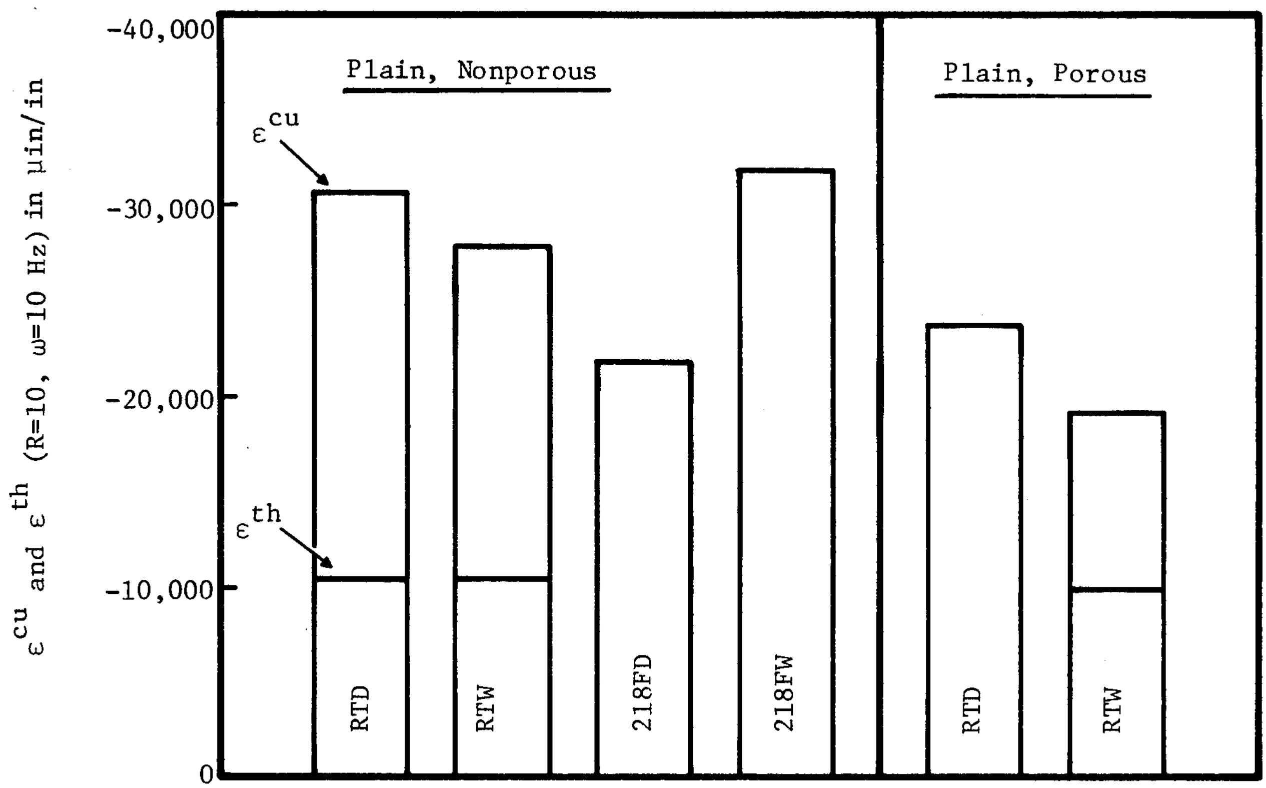


Figure 3. Compression Data on $[\pm 45]_{6S}$ Specimens.

TABLE 4. SUMMARY OF COMPRESSION DATA ON $[0_{16}/\underline{+}45_5/90_4]_c$ AS/3501-6 SPECIMENS.

Specimen Type	Environment	ε^{cu}(thin)* (μin/in)	ε^{cu}(thick)* (μin/in)	ε^{th}(thin)† R, ω=10	ε^{th}(thick)+ R, ω=10
Plain, Nonporous	RTD	-11,816	-11,816	- 9,000	- 9,000
	RTW	-10,478	-10,478	- 8,250	- 8,250
	218FD	- 9,637	- 9,637	--	--
	218FW	- 8,381	- 8,381	- 7,050	- 7,050
	-65FW	-13,533	-13,533	-10,500	-10,500
Plain, Porous	RTD	- 9,538	- 9,538	- 7,600	- 7,600
	RTW	- 8,965	- 8,965	- 8,100	- 8,100
	218FW	- 6,213	- 6,213	- 5,700	- 5,700
Nonporous, Two 0^o plies dropped	RTD	-13,217		- 7,000	-6,250
	RTW	-13,965	-11,925	- 6,800	-5,150
	218FW	- 8,300		- 6,100	-4,400
	-65FW	-17,100		- 9,100	-7,150
Nonporous, Four $\underline{+}45^o$ plies dropped	RTD	-12,183		- 7,900	-7,500
	RTW	-10,675		- 5,570	-5,095
	218FW	- 9,117		- 6,400	-5,200
	-65FW	-13,650		- 9,400	-7,430
Porous, Two 0^o plies, dropped	RTW	-13,220	-11,320	---	---

TABLE 4. SUMMARY OF COMPRESSION DATA ON $[0_{16}/\pm45_5/90_4]_c$ AS/3501-6 SPECIMENS (CONCLUDED)

Specimen Type	Environment	ε^{cu}(thin)* (μin/in)	ε^{cu}(thick)* (μin/in)	ε^{th}(thin)+ R, ω=10	ε^{th}(thick)+ R, ω=10
Nonporous, Two 0^o plies dropped, 3/16" dia. open hole	RTW	- 7,035	- 6,125	- 4,360	-3,860
Nonporous, Two 0^o plies dropped, 3/16" dia. hole, bolt load=0.1 x total load	RTW	- 6,950	- 5,730	- 4,900	- 4,120
Porous, Two 0^o plies dropped, 3/16" dia. open hole	RTW	- 6,125	- 5,725	- 4,300	- 4,040
Porous, Two 0^o plies dropped, 3/16" dia. hole, bolt/total load= 0.1	RTW	- 6,730	- 6,180	- 4,560	- 4,270

* ε^{cu}(thin) and ε^{cu}(thick) correspond to the ultimate compressive strains in the thinner and thicker sections of the ply drop-off specimens.

\+ ε^{th}(thin) and ε^{th}(thick) are the threshold strain levels in the thinner and thicker sections of the ply drop-off specimens, below which no fatigue failure occurs for at least 1.25×10^6 cycles at R=10 and ω=10 Hz.

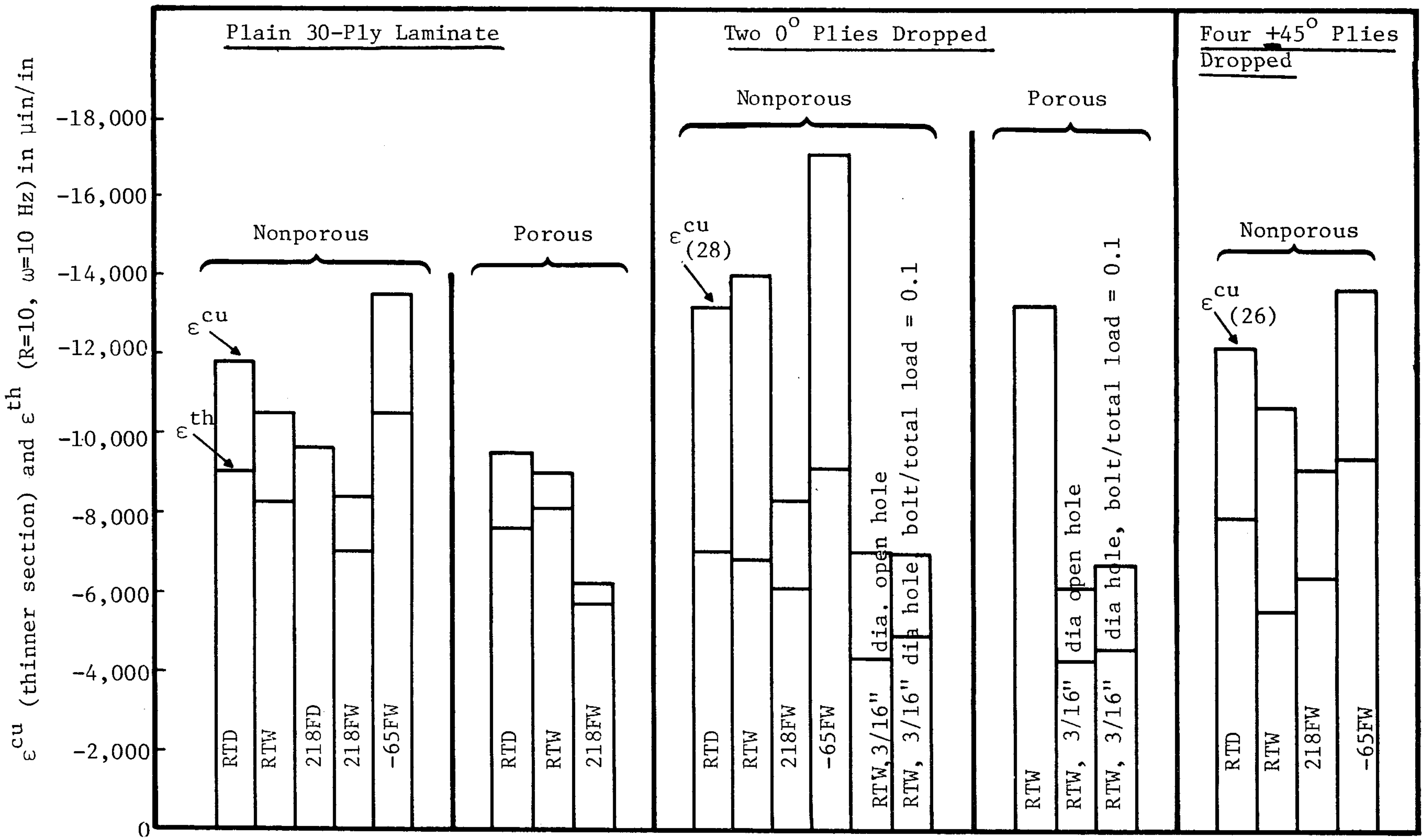


Figure 4. Compression Data on $[0_{16}/\pm 45_5/90_4]_c$ Specimens.

significantly when a 3/16 in. diameter hole is drilled at the ply drop-off location. A partially loaded fastener at the hole does not affect the strain concentration significantly under compressive loading. When a uniform porosity level of 2.5 to 4.5% by volume exists in this laminate, a slight additional reduction in the ε^{cu} is measured.

SECTION 2

DESCRIPTION OF EXPERIMENTAL PROGRAM

2.1 Fabrication of Test Panels

Table 5 presents a list of the tests that were conducted in the program. Test panels were fabricated using Northrop Specification Type I (42% resin content by weight), AS1/3501-6 graphite/epoxy prepreg material. The same material was used in three previous Northrop/Navy programs (References 1 to 3). The material passed the acceptance requirements (presented in Appendix A) as per the vendor-supplied data that accompanied the material. The prepreg resin and volatile contents, its flow, gel time and tack were all acceptable. A 16-ply unidirectional laminate ($[0]_{16T}$) was fabricated to conduct quality control (QC) tests. Results from these tests are presented in Tables 6, 7, and 8. The physical properties in Table 6 and the mechanical properties in Tables 7 and 8 compare well with data obtained in Reference 1. The test material was therefore judged to be adequate for the program.

Two panels were fabricated, per the fabrication work order in Appendix A, with a 30-ply layup over half the planform and a 28-ply layup over the other half. The thinner section was obtained by dropping off two 0° plies (see Figures A1 and A2). A similar laminate was tested in Reference 2. One of the two laminates was cured under vacuum plus 15 psi conditions to introduce uniform porosity in it (see Reference 3). The other laminate was cured using the standard cycle (100 psi) to produce a good quality laminate. The test panels are representative of an F-18/A vertical tail skin layup at the aft mid-rib location.

Fabricated program panels were inspected via ultrasonic through-transmission to determine their quality. The nonporous (NP) laminate produced a C-scan with no indications of flaws in it (Figure 5), and a C-scan of the porous (P) laminate indicated the presence of uniform porosity in it (Figure 6). The C-scan record of the nonporous panel was obtained at 5 MHz and 10 dB, while the C-scan record of the porous panel was obtained at 5 MHz and 22 dB. Figures 5 and 6 look similar to the C-scan records presented in Reference 3.

TABLE 5. PROGRAM TEST MATRIX

Test Series	Laminate Type*	Specimen Type	Test Conditions	Loading+	No. of Specimens
1	Nonporous	Plain	RTW++	SC	3
2	Porous	Plain		SC	3
3	Nonporous	Open Hole		SC	3
4	Porous	Open Hole		SC	3
5	Nonporous	Open Hole		CAF	6
6	Porous	Open Hole		CAF	6
7	Nonporous	Partially Loaded Hole		SC	3
8	Porous	Partially Loaded Hole		SC	3
9	Nonporous	Partially Loaded Hole		CAF	6
10	Porous	Partially Loaded Hole		CAF	6
				TOTAL	42

Test specimens are 8-in long and 2-in wide (see Figure A3).

*Test specimens are 30 plies-thick (of a $[0_{16}/\pm45_5/90_4]_c$ configuration) over half the length and 28 plies-thick (of a $[0_{14}/\pm45_5/90_4]_c$ configuration) over the other half.

The 30-ply region has a $[\mp45/0/(90/0_3)_2/\mp45/0/45^Q]_S$ layup, and the 28-ply region has a $[\mp45/0/90/0_3/90/0_2/\mp45/0/45^Q]_S$ layup. Ply numbers 9 and 22 (0^0 plies) end at specimen mid length.

+SC - static compression

CAF - constant amplitude fatigue (R=10; ω = 10 Hertz)

++RTW - room temperature, wet conditions (1.3% moisture by weight).

TABLE 6. PHYSICAL PROPERTIES OF $[0]_{16T}$ AS1/3501-6 QC SPECIMENS (CHEMICAL ANALYSIS)

Specimen	Laminate Specific Gravity	Resin Content (% by wt.)	Resin Content* (% by vol.)	Fiber Content* (% by vol.)	Void Content* (% by vol.)
P-1	1.5911	28.74	36.29	62.99	0.72
P-2	1.5871	29.30	36.90	62.34	0.76
P-3	1.5910	29.08	36.73	62.68	0.59
Average →	1.5897	29.04	36.64	62.67	0.69

* These are computed using specific gravity values of 1.80 and 1.26 for the fiber and the resin, respectively.

TABLE 7. STATIC TENSION TEST DATA ON $[0]_{8T}$ AS1/3501-6 QC SPECIMENS

Specimen	Test Temperature	Width (in.)	Thickness (in.)	Area (in^2)	Failure Load (lb)	Ultimate Stress (ksi)	Modulus (Msi)	Ultimate Strain * (μin/in)
RT-1	Ambient	.500	.044	.0220	5500	250.0	20.85	11,990
RT-2	↓	.501	.046	.0231	5700	246.8	--	--
RT-3	↓	.500	.045	.0225	5050	224.4	17.36	12,926
				Average →		240.4	19.11	12,458
ET-1	250F	.500	.045	.0225	4770	212.0	18.94	11,193
ET-2	↓	↓	↓	↓	5600	248.9	20.83	11,949
ET-3	↓	↓	↓	↓	5220	232.0	18.32	12,664
				Average →		231.0	19.36	11,935

* Obtained assuming a linear stress-strain behavior to failure

TABLE 8. SHORT BEAM SHEAR DATA ON $[0]_{16}$ AS/3501-6 QC SPECIMENS

Specimen	Test Tempera-ture	Width (in)	Thickness (in)	Area, A (in.^{2})	Beam Span (in.)	Failure Load, P (lb)	$\tau_{ult} = \frac{3P}{4A}$ (ksi)
S-1	Ambient	.250	.079	.0198	0.30	490	18.560
S-2	↓	↓	↓	↓	↓	484	18.330
S-3						500	18.940
						Average →	18.610
S-4	250F	.250	0.077	0.193	0.30	352	13.680
S-5	↓	↓	↓	↓	↓	339	13.170
S-6						323	12.550
						Average →	13.133

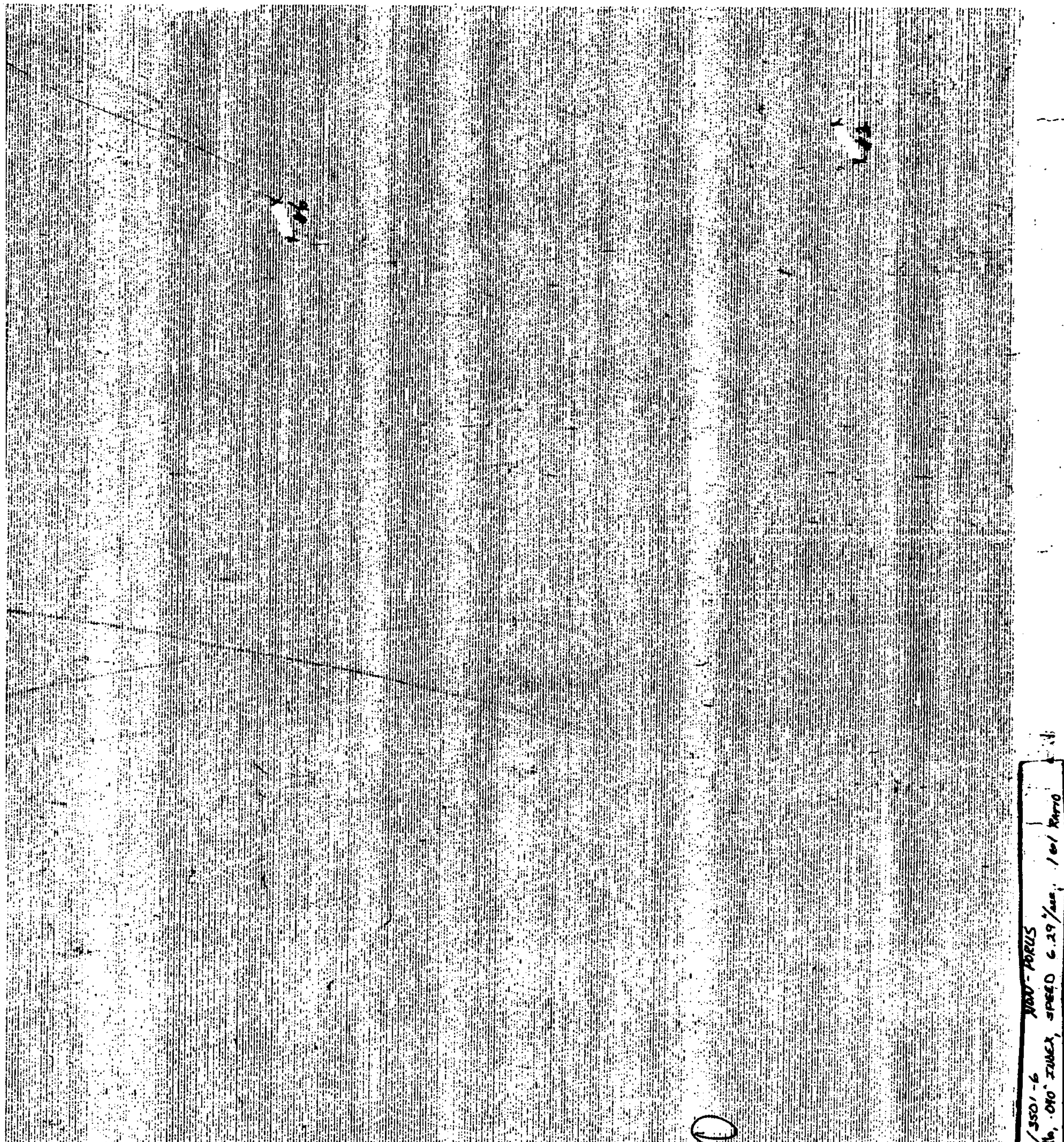


Figure 5. Ultrasonic C-scan Record of the Nonporous Panel.

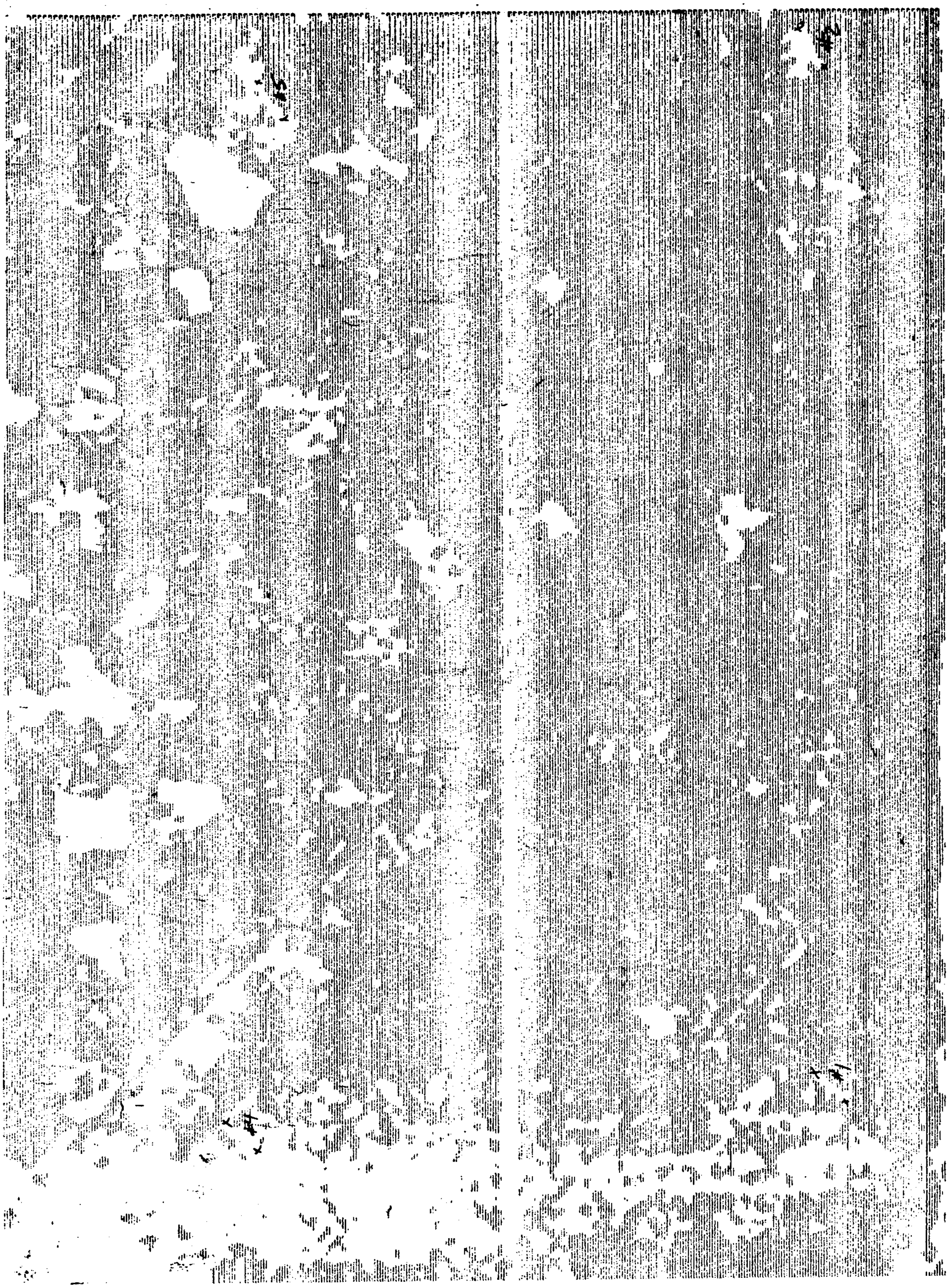


Figure 6. Ultrasonic C-scan Record of the Porous Panel.

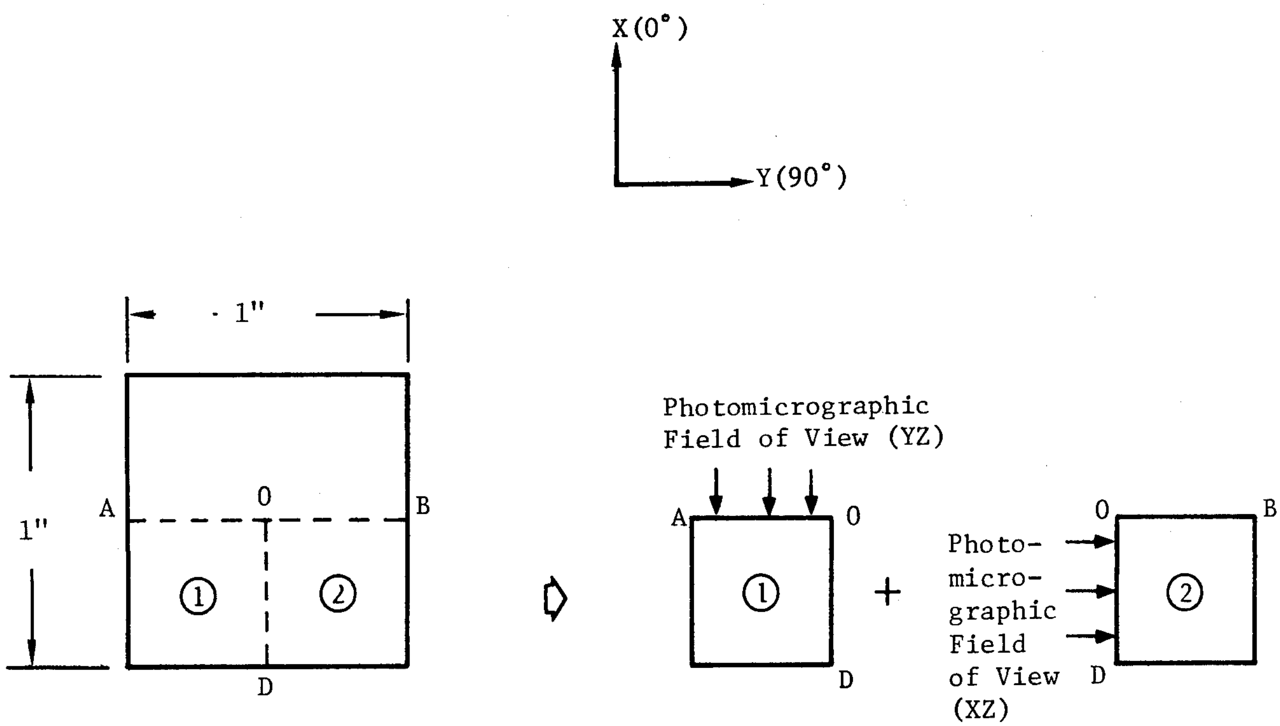
2.2 Computation of Void Content in the Porous Panel

Void content (porosity) measurements were carried out on 1-in. square specimens from the porous and nonporous laminates. Figure A1 shows the locations from which these specimens were extracted. Two methods were employed to compute the void volume percentages in the laminates. The first method used an image analysis system on 25X photomicrographs of cross-sections of program laminates, and computed areal percentages of voids which were assumed to approximate the void volume percentages. The second method involved a chemical analysis where the specimens were weighed in air and in water, the resin material was subsequently dissolved in an acid solution, specific gravities of the fiber reinforcement and the resin material were assumed, and void volume percentages computed as shown in Appendix B.

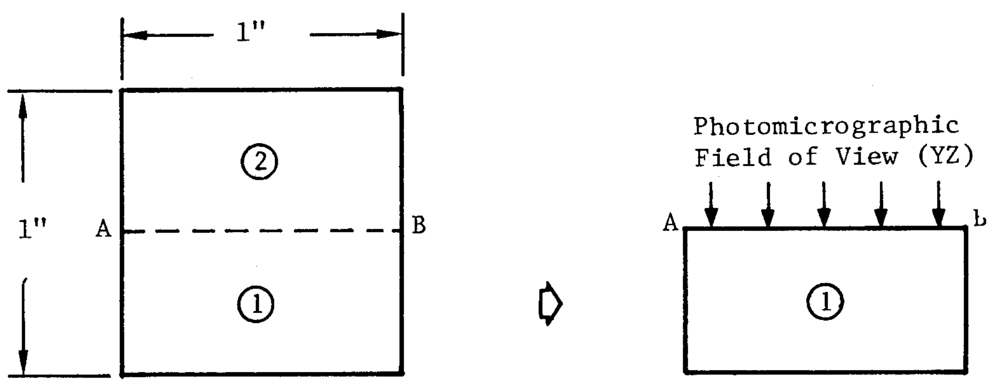
Figure 7 shows the cross-sections of the 1-in. square specimens (porous and nonporous) that were inspected via image analysis of photomicrographs. Only the YZ cross-sections of nonporous specimens were inspected, while YZ and XZ cross-sections of porous specimens were inspected. Each specimen was mounted and photographed at a magnification factor of 25 (see Figures B1 and B2). The mounts were then coated with gold (approximately 600 Å in thickness) by sputter deposition. This increased the reflectivity of the nonporous polished surface without increasing the reflectivity of the pores, dramatically increasing the contrast between the pores and the matrix so that the image analyzer can detect the pores more precisely. Porosity measurement was then performed using a Bausch and Lomb FAS II Image Analysis system interfaced to a Leitz MM5 metallograph. Each measurement was integrated over nine fields of view, each field measuring 1319 by 1019 micrometers. The one-sigma sampling error was calculated using the formula:

$$\text{Standard deviation} = 1.1/\sqrt{\text{Number of pores}}$$

Table 9 lists the measured areal percentages of voids in the porous and nonporous specimens. These are approximately equal to the void volume percentages. It is seen that the "nonporous" laminates contained a negli-



(a) Porous Specimens



(b) Non porous Specimens

Figure 7. Fields of View for Image Analysis of Photomicrographs of Porous and Non porous Specimens.

TABLE 9. VOID CONTENT MEASUREMENTS THROUGH IMAGE ANALYSIS OF 25X PHOTOMICROGRAPHS

Specimen	Section	Field-to-field variation in APV			Areal Percentage of Voids (Average of 9 fields)
		Minimum	Maximum	Deviation	
PV1B	OA	2.2	6.0	1.3	3.8 ± 0.4
	OD	2.2	13.7	4.3	6.4 ± 0.7
PV2B	OA	2.6	12.7	3.6	7.6 ± 0.6
	OD	2.1	7.0	1.4	3.6 ± 0.3
PV3B	OA	1.0	5.5	1.2	3.1 ± 0.3
	OD	< 0.05	11.3	3.6	4.3 ± 0.5
PV4B	OA	2.1	11.4	2.7	4.9 ± 0.3
	OD	1.1	5.3	1.4	3.4 ± 0.3
PF3	OA	2.0	6.8	1.4	4.2 ± 0.3
	OD	2.1	6.4	1.2	4.0 ± 0.4
PF2	OA	2.7	9.4	2.2	5.3 ± 0.3
	OD	2.0	4.7	0.9	3.4 ± 0.3
Average	→	--	--	--	4.5
NPV1B	AB	--	--	--	0.040 ± 0.001
NPV2B	AB	--	--	--	0.011
NPV3B	AB	--	--	--	0.042 ± 0.006
NPV4B	AB	--	--	--	0.015
NPF3	AB	--	--	--	0.029
NPF2	AB	--	--	--	0.059 ± 0.003
Average	→	--	--	--	0.033

gible (0.033%) void content, while the porous laminates contained an average void volume percentage of 4.5, as measured by the image analyzer.

Void volume computation based on chemical analysis measurements is very dependent on accurate fiber and resin density values. Program laminates were built from a lot of prepreg material (Hercules Lot No. 60052099) in which the specific gravity of the fiber (SGF) varied from 1.7715 to 1.8269, with a lot average of 1.8103. Quality control physical properties for $[0]_{16T}$ specimens were computed earlier (see Table 6) based on fiber and resin specific gravities of 1.80 and 1.26 respectively. Small changes in these specific gravity values result in large changes in the computed void volume percentages. Chemical analysis measurements were made on 1-in square specimens from program laminates, and Tables 10, 11 and 12 list the computed physical properties for three sets of fiber and resin density values (SGF and SGR, respectively). Among these, the computations corresponding to SGR = 1.27 and SGF = 1.81 yield the lowest void volume measurements for the nonporous laminates (0.19%). The corresponding average void content in the porous laminates is approximately 2.5% by volume. This is lower than the 4.5% areal percentage value obtained using an image analyzer (Table 9).

An inspection of the photomicrographs in Appendix B (Figures B1 and B2), and those in Reference 3, indicates that microvoids are predominantly present at interfacial locations. Also, they seem to be tubular in form, with the axis of the tube lying along the fiber orientation in an adjacent ply. Therefore, an image analysis of photomicrographs of the XZ and YZ cross-sections alone (Figure 7) may not suffice to yield a good estimate of the void content in the panels. Sections at 45° orientation to the XZ and YZ planes should also be examined. This, however, was not done in the reported program. Also, a reliable computation of the void content based on chemical analysis requires an accurate measurement of fiber and resin densities in the test panel. No technique is currently available to make such a measurement. Hence the discrepancy between the void content measurements based on chemical analysis and image analysis. It is believed that the actual void content in the porous laminates of this program, and those in Reference 3, lies between 2.5% and 4.5% by volume.

TABLE 10. PHYSICAL PROPERTIES OF PROGRAM LAMINATES (SGR=1.26; SGF=1.80)--CHEMICAL ANALYSIS

Specimen	Laminate Specific Gravity	Resin Content (% by wt.)	Resin Content (% by vol.)	Fiber Content (% by vol.)	Void Content (% by vol.)
NPV1	1.5902	32.10	40.52	59.98	-0.50
NPV2	1.5826	33.18	41.67	58.75	-0.42
NPV3	1.5815	33.76	42.37	58.20	-0.57
NPV4	1.5869	32.80	41.31	59.24	-0.55
NPF1	1.5573	37.43	46.26	54.13	-0.39
NPF4	1.5659	35.89	44.60	55.77	-0.37
Average →	1.5774	34.19	42.79	57.68	-0.47
PV1	1.5429	34.03	41.68	56.54	1.78
PV2	1.5582	31.62	39.10	59.19	1.71
PV3	1.5445	33.24	40.74	57.29	1.97
PV4	1.5595	30.14	37.31	60.52	2.17
PF1	1.5275	36.34	44.06	54.02	1.92
PF4	1.5297	36.36	44.15	54.08	1.77
Average →	1.5437	33.62	41.17	56.94	1.89

Specific gravity of resin = 1.26 Specific gravity of fiber = 1.80

TABLE 11. PHYSICAL PROPERTIES OF PROGRAM LAMINATES (SGR=1.27; SGF=1.81)--CHEMICAL ANALYSIS

Specimen	Laminate Specific Gravity	Resin Content (% by wt.)	Resin Content (% by vol.)	Fiber Content (% by vol.)	Void Content (% by vol.)
NPV1	1.5902	32.10	40.20	59.65	0.15
NPV2	1.5826	33.18	41.35	58.42	0.23
NPV3	1.5815	33.76	42.03	57.88	0.08
NPV4	1.5869	32.80	40.99	58.91	0.10
NPF1	1.5573	37.43	45.90	53.83	0.27
NPF4	1.5659	35.89	44.25	55.47	0.28
Average →	1.5774	34.19	42.45	57.36	0.19
PV1	1.5429	34.03	41.35	56.23	2.42
PV2	1.5582	31.62	38.80	58.87	2.34
PV3	1.5445	33.24	40.42	56.97	2.61
PV4	1.5595	30.14	37.01	60.19	2.80
PF1	1.5275	36.34	43.71	53.72	2.57
PF4	1.5297	36.36	43.80	53.78	2.42
Average →	1.5437	33.62	40.85	56.63	2.53

Specific gravity of resin = 1.27 Specific gravity of fiber = 1.81

TABLE 12. PHYSICAL PROPERTIES OF PROGRAM LAMINATES (SGR=1.29; SGF=1.81)--CHEMICAL ANALYSIS

Specimen	Laminate Specific Gravity	Resin Content (% by wt.)	Resin Content (% by vol.)	Fiber Content (% by vol.)	Void Content (% by vol.)
NPV1	1.5902	32.10	39.58	59.65	0.77
NPV2	1.5826	33.18	40.71	58.42	0.87
NPV3	1.5815	33.76	41.38	57.88	0.74
NPV4	1.5869	32.80	40.35	58.91	0.74
NPF1	1.5573	37.43	45.19	53.83	0.98
NPF4	1.5659	35.89	43.56	55.47	0.97
Average →	1.5774	34.19	41.80	57.36	0.85
PV1	1.5429	34.03	40.71	56.23	3.06
PV2	1.5582	31.62	38.19	58.87	2.94
PV3	1.5445	33.24	39.79	56.97	3.24
PV4	1.5595	30.14	36.44	60.19	3.37
PF1	1.5275	36.34	43.03	53.72	3.25
PF4	1.5297	36.36	43.12	53.78	3.10
Average →	1.5437	33.62	40.21	56.63	3.16

Specific gravity of resin = 1.29 Specific gravity of fiber = 1.81

2.3 Test Specimen Preparation

Test specimens were extracted from fabricated porous and nonporous panels in accordance with the Test Work Order in Appendix A. Panels were block-machined, tabbed and machined again to obtain the test specimens for the program. The ends of the 8 in. long, 2 in. wide specimens (see Figure A3) were ground to be flat and parallel, within achievable tolerance limits, for proper introduction of compressive loads through end-bearing. In 20 specimens, identified in the Fabrication Work Order, 3/16 in. diameter (+ 0.003 in, - 0.0 in) holes were drilled at the center (the ply drop-off location). All the specimens, along with 1-in square moisture travelers, were dried in an oven at 170^{o}F for approximately 10 hours. The free edges and hole boundaries (if any) of the specimens and travelers were sealed using aluminum tape. The travelers were then weighed, and the specimens and travelers exposed to a 170^{o}F, 95% relative humidity (RH) environment for 63 days, followed by an exposure to a 170^{o}F, 80% RH environment for an additional 36 days. Appendix B contains the traveler moisture data (Tables B1 and B2). The nonporous and porous test specimens absorbed approximately 1.3% of moisture by weight. This represents near equilibrium level moisture content in the test specimens, for the simulated environment, distributed in a nearly uniform manner across the thickness. Moisture-conditioned specimens were sealed in aluminum foil bags to retain absorbed moisture until they were ready to be tested. Prior to testing, back-to-back axial and transverse strain gages were bonded to the specimens at specified locations (see the Test Work Order in Appendix A).

2.4 Test Setups

Tests performed in this program include static compression tests on 3-in long, 2-in wide QC specimens, and tests on 8-in long, 2-in wide (see Figure A3) specimens per Table 5. The tests listed in Table 5 include static compression and compression fatigue ($R = 10$, $\omega = 10$ Hertz) tests on plain specimens, specimens with an unloaded 3/16 in. diameter central hole at the ply drop-off location, and specimens with a fastener bearing load equal to 10% of the total applied load. In each specimen, the ply drop-off was located at the center of the test length. Half the specimens were defect-free and the other half had uniform porosity induced by a 15 psi cure cycle.

Static compression tests on the 3-in long, 2-in wide QC specimens were conducted in the text fixture shown in Figure A4. Static compression tests on the 8-in long, 2-in wide specimens were conducted in the setup shown in Figures 8 and 9. A fraction (0.1) of the total load was introduced directly at the fastener location through the arrangement shown in Figure 10.

Constant amplitude compression fatigue tests on porous and nonporous specimens were conducted at an algebraic minimum to maximum cyclic load ratio (R) of 10, and at a frequency (ω) of 10 Hertz. The fatigue test setups are shown in Figures 11 to 13.

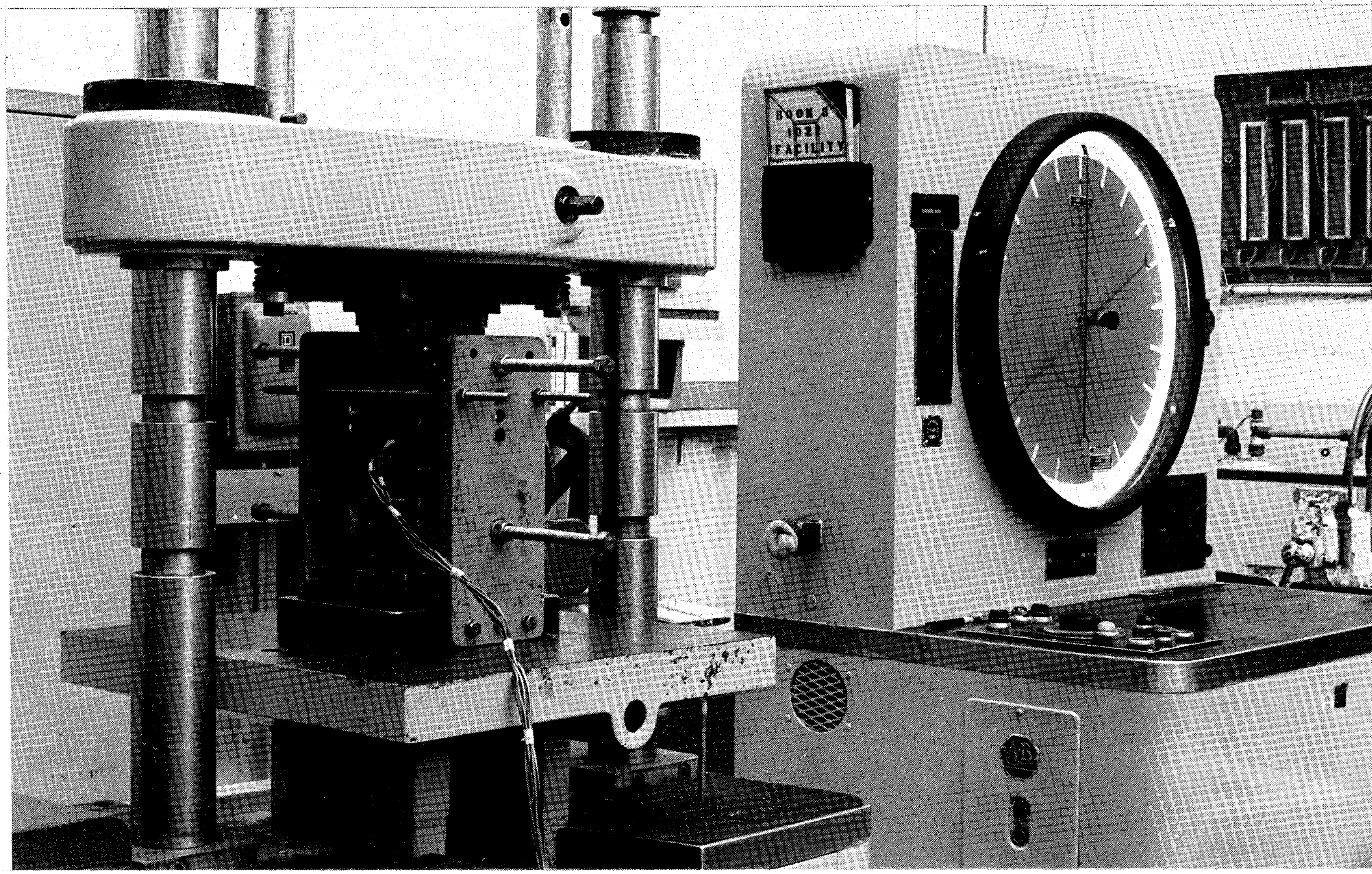


Figure 8. Static Compression Test Setup.

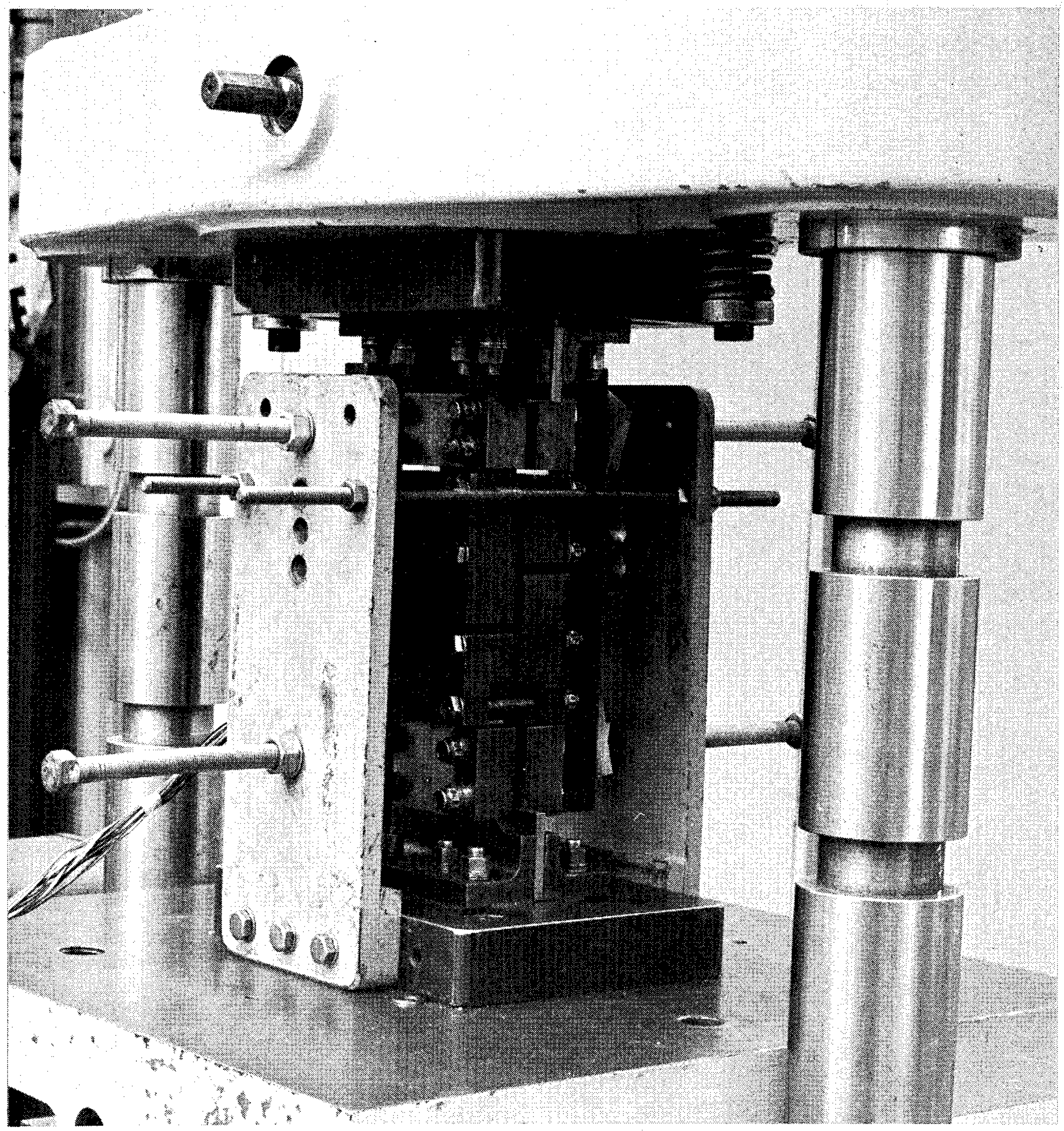


Figure 9. Close-up of the Static Compression Test Setup.

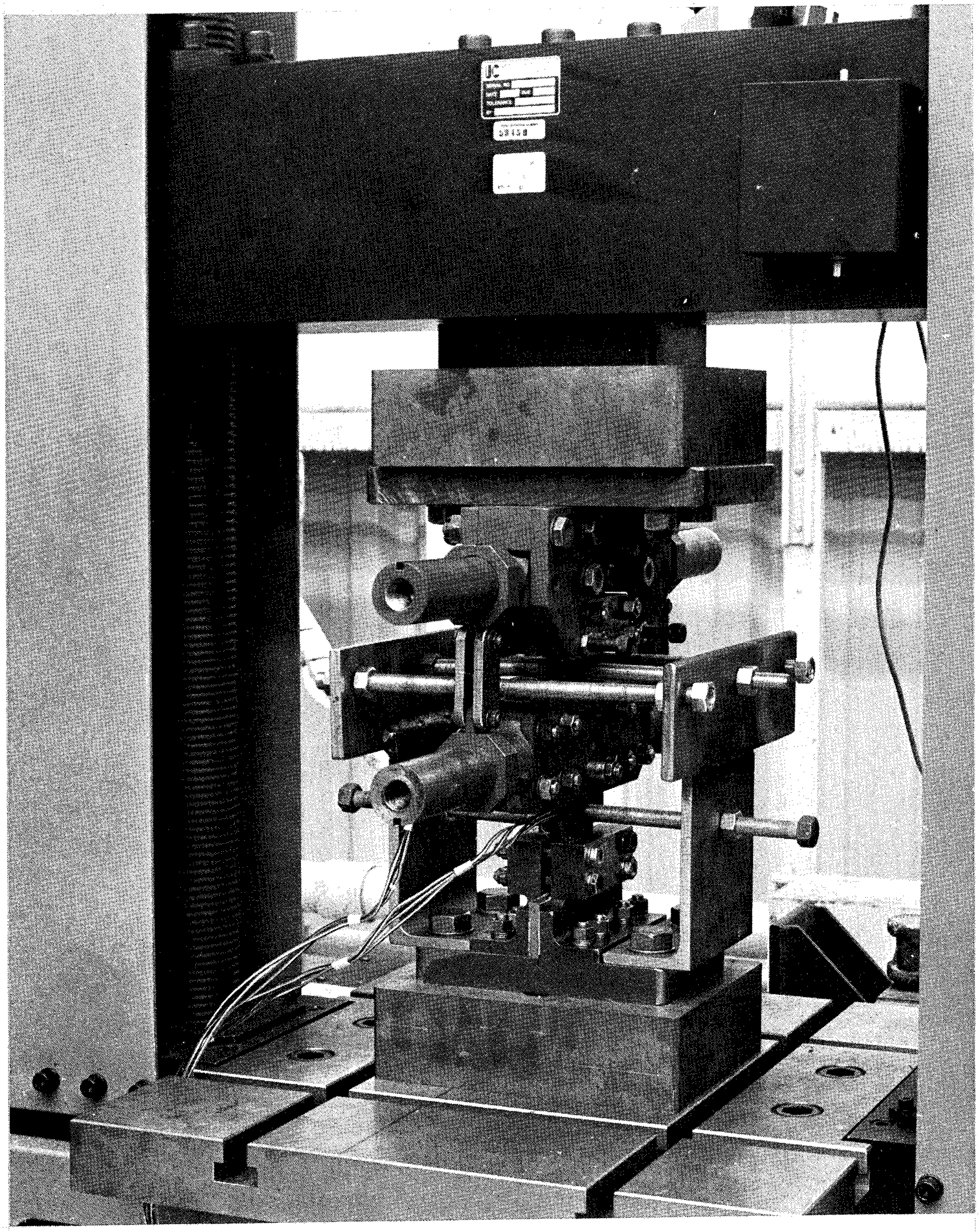


Figure 10. Static Compression Test Setup for Specimens with Partially Loaded Holes.

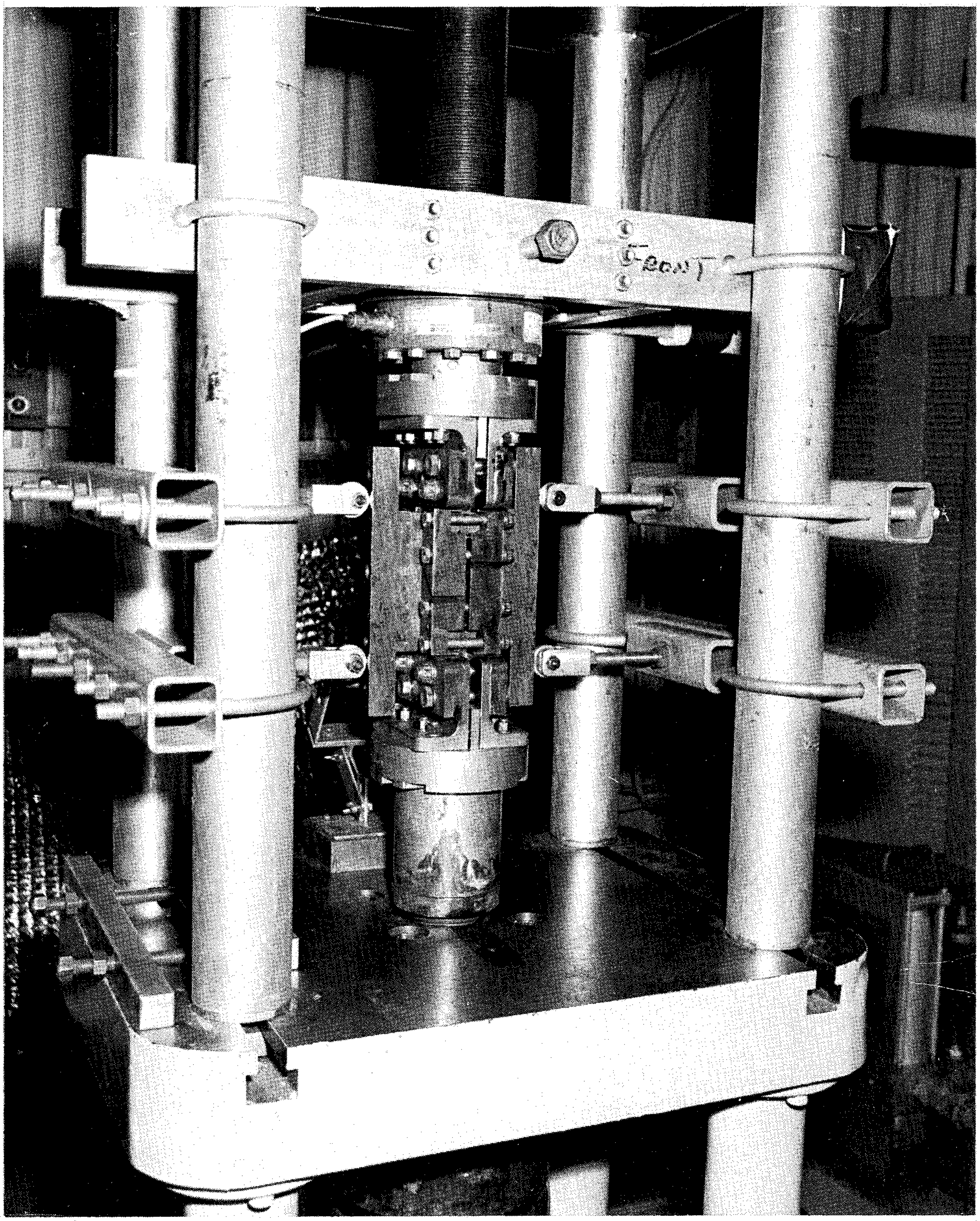


Figure 11. Compression Fatigue Test Setup.

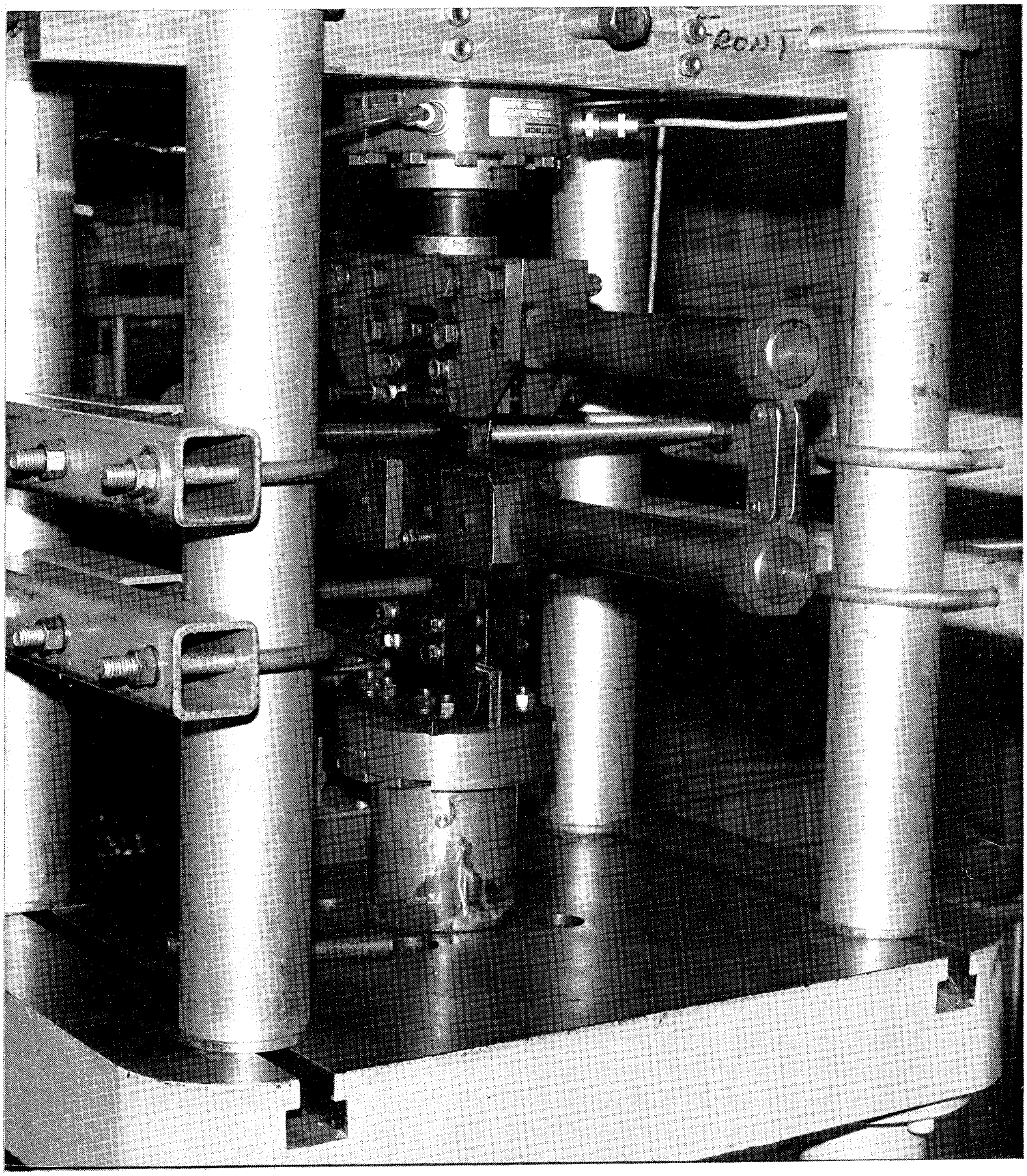


Figure 12. Compression Fatigue Test Setup for Specimens with Partially Loaded Holes.

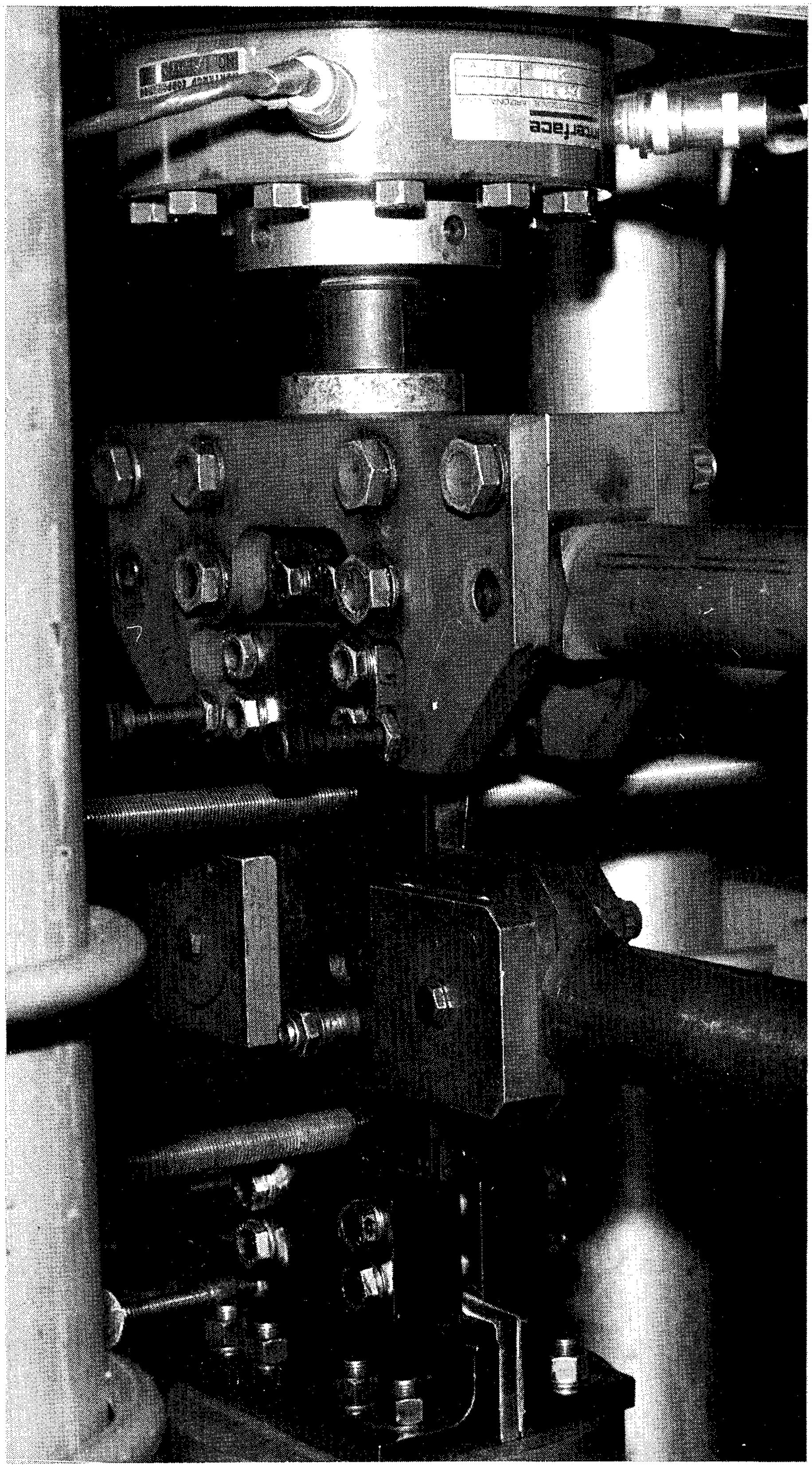


Figure 13. Close-up of the Compression Fatigue Test Setup for Specimens with Partially Loaded Holes.

SECTION 3

DISCUSSION OF RESULTS

3.1 RTD Static Compression Test Results on QC Specimens

Table 13 presents the RTD static compression test results on the 3 in. long, 2 in. wide QC specimens. Specimens labeled PLC and NPLC were loaded in the 0^{o} (longitudinal) direction, while specimens labeled PTC and NPTC were loaded in the 90^{o} (transverse) direction. From the longitudinal test results it is seen that the induced porosity causes a 24% reduction in the compressive strength of $[0_{16}/\pm45_5/90_4]_c$ specimens, and a 22% reduction in the strength of $[0_{14}/\pm45_5/90_4]_c$ specimens.

3.2 RTW Static Compression Test Results

A summary of the RTW static compression test results on the 8 in. long, 2 in. wide specimens is presented in Table 14. Two out of three replicates corresponding to each test case were monitored using back-to-back axial and transverse strain gages, located in the 28-ply and the 30-ply sections. Stress-strain curves from the various tests are presented in Appendix C (Figures C1 to C10).

In plain specimens with a ply drop-off, the ultimate compressive strain (ε^{cu}) in the 28-ply section decreases from -13,965 to -13,220 μin/in when porosity is introduced. A 5.3% reduction in $\varepsilon^{cu}(28)$ is therefore induced by porosity. In nonporous specimens, a 49.6% reduction in $\varepsilon^{cu}(28)$ is caused by a 3/16 in. diameter unloaded (open) hole. An additional 12.9% reduction in the nonporous, open hole $\varepsilon^{cu}(28)$ value is caused by the induced porosity. The introduction of a fastener load (10% of the total load) causes a negligible reduction (1%) in the open hole $\varepsilon^{cu}(28)$ for nonporous specimens, and a 10% increase in the open hole $\varepsilon^{cu}(28)$ for porous specimens. A similar effect is noted on the ε^{cu} value in the 30-ply section for the discussed cases. Figure 4 compares the effects of porosity, unloaded hole and partially loaded hole on $\varepsilon^{cu}(28)$ in a bar chart format.

TABLE 13. RTD QUALITY CONTROL COMPRESSION TEST RESULTS.

Laminate Type	No. of Plies in QC Specimen	Specimen ID*	Average Area (in^2)	Loading Direction	Failure Load (kips)	Compressive Strength (ksi)	Average Compressive Strength (ksi)	Porous Strength/ Nonporous Strength
Nonporous (ACL4876)	30	NPTC-1	0.3701	90^0	-23.65	-63.902	-63.706	1.00
	30	NPTC-2	0.3176	90^0	-23.60	-63.509		
	28	NPTC-3	0.3450	90^0	-20.00	-57.971	-59.954	1.00
	28	NPTC-4	0.3439	90^0	-21.30	-61.937		
Nonporous (ACL4876)	28	NPLC-1	0.3422	0^0	-32.3	-94.389	-98.715	1.00
	28	NPLC-2	0.3387	0^0	-34.9	-103.041		
	30	NPLC-3	0.3729	0^0	-36.2	-97.077	-96.254	1.00
	30	NPLC-4	0.3699	0^0	-35.3	-95.431		
Porous (ACL4877)	30	PTC-1	0.3699	90^0	-18.70	-50.554	-52.000	0.8162
	30	PTC-2	0.3686	90^0	-19.70	-53.445		
	28	PTC-3	0.3449	90^0	-20.30	-58.858	-60.101	1.0025
	28	PTC-4	0.3456	90^0	-21.20	-61.343		
Porous (ACL4877)	28	PLC-1	0.3501	0^0	-27.40	-78.263	-75.150	0.7613
	28	PLC-2	0.3526	0^0	-25.40	-72.036		
	30	PLC-3	0.3752	0^0	-26.70	-71.162	-75.009	0.7793
	30	PLC-4	0.3741	0^0	-29.50	-78.856		

* Specimens with "TC" in their ID were subjected to transverse compression loading (90^0 direction), and those with "LC" were subjected to longitudinal compression loading (0^0 direction).

TABLE 14. SUMMARY OF RTW STATIC COMPRESSION TEST RESULTS.

Test Series	Specimen Type	Specimen ID	Failure Load (kips)	Compressive Strengths (ksi) $\sigma_x^{cu}(30)^+$	$\sigma_x^{cu}(28)^+$	Compressive Failure Strain (μin/in) $\varepsilon_x^{cu}(30)^+$	$\varepsilon_x^{cu}(28)^+$	Compressive Modulus (Msi) $E_x^c(30)^+$	$E_x^c(28)^+$	Poisson's Ratio, ν_{xy} $\nu(30)^+$	$\nu(28)^+$
1	Nonporous, Plain	NP-1	-40.700	-108.418	-114.390	-12,350	-14,680	9.970	8.980	0.361	0.325
		NP-2	-36.800	- 99.837	-107.414	-11,500	-13,250	9.793	9.479	0.335	0.336
		NP-3	-38.800	-103.581	-113.460	--	--	--	--	--	--
		Average	→	-103.945	-111.755	-11,925	-13,965	9.882	9.230	0.348	0.331
2	Porous, Plain	P-1*	-28.400	- 76.939	- 82.196	- 8,120	- 9,150	10.695	11.236	0.241	0.183
		P-2	-35.800	- 97.177	-104.495	-11,320	-13,220	9.912	9.027	0.336	0.346
		P-3	-36.500	- 98.920	-106.299	--	--	--	--	--	--
		Average	→	- 98.049	-105.397	-11,320	-13,220	9.912	9.027	0.336	0.346
3	Nonporous, Open Hole (3/16" dia)	NP-4	-26.000	- 69.970	- 75.237	- 6,230	- 7,780	11.231	9.661	0.316	0.272
		NP-5	-24.000	- 65.829	- 71.139	- 6,020	- 6,290	10.920	11.380	0.309	0.355
		NP-6	-24.400	- 67.895	- 73.590	--	--	--	--	--	--
		Average	→	- 67.898	- 73.322	- 6,125	- 7,035	11.076	10.521	0.313	0.314
4	Porous, Open Hole (3/16" dia)	P-4	-22.000	- 59.524	- 63.953	- 5,500	- 5,820	10.818	11.009	0.281	0.279
		P-5	-23.200	- 61.280	- 66.633	- 5,950	- 6,430	10.303	10.358	0.286	0.287
		P-6	-23.800	- 63.568	- 67.232						
		Average	→	- 61.457	- 65.939	- 5,725	- 6,125	10.561	10.684	0.284	0.283
7	Nonporous, bolt load/total load=0.1	NP-13**	-21.229	- 57.847	- 62.188	--	--	--	--	--	--
		NP-14	-24.780	- 66.828	- 73.054	- 5,730	- 6,950	11,667	10.526	0.311	0.346
		NP-15	-25.584	- 69.563	- 75.077	--	--	--	--	--	--
		Average	→	- 68.196	- 74.066	- 5,730	- 6,950	11.667	10.526	0.311	0.346
8	Porous, bolt load/total load=0.1	P-13**	-21.581	- 57.889	- 61.979	--	--	--	--	--	--
		P-14	-24.374	- 65.206	- 69.920	- 6,180	- 6,730	10.574	10.389	0.356	0.286
		P-15	-24.970	- 66.908	- 71.506	--	--	--	--	--	--
		Average	→	- 66.057	- 70.713	- 6,180	- 6,730	10.574	10.389	0.356	0.286

*Test data from this specimen were not used to compute averages. The low compressive strength of this specimen is probably due to a higher level of porosity in it than in the other specimens (Back-to-back axial gages confirmed negligible bending effects).

**These specimens were initially tested such that the fastener carried 25% of the total applied load. Fastener failures resulted, damaging these specimens slightly. They were then retested such that the fastener load was only 10% of the total applied load. Results from retested damaged specimens were not considered when averages were calculated.

+ $\sigma_x^{cu}(30)$, $\varepsilon_x^{cu}(30)$, $E_x(30)$, $\nu(30)$ = **strength, failure strain, modulus and Poisson's ratio corresponding to the 30-ply thickness region.**

+ $\sigma_x^{cu}(28)$, $\varepsilon_x^{cu}(28)$, $E_x(28)$, $\nu(28)$ = **strength, failure strain, modulus and Poisson's ratio corresponding to the 28-ply thickness region.**

Failed plain and open (unloaded) hole specimens, both porous and nonporous, are shown in Figure 14 (the top half). These correspond to test series 1 to 4 in Table 5. Failed specimens with partially loaded holes, both porous and nonporous, are shown in Figure 15. The failure mode in each test case is the expected failure across the width of the specimen.

3.3 RTW Compression Fatigue Test Results

Constant amplitude compression fatigue tests were conducted at R = 10 and ω = 10 Hertz. The minimum cyclic stress values were selected for the tests based on static test results (see Table 14). Specimens that survived a million cycles of the imposed fatigue loading were labeled "run-out" specimens. The maximum absolute cyclic stress amplitude at which a specimen "runs out" is referred to as the fatigue "threshold" stress level.

Tables 15 and 16 present the RTW fatigue test results on nonporous and porous test specimens with unloaded 3/16. in. diameter central holes. Figures 16 and 17 are plots of minimum cyclic strain versus cycles to failure, corresponding to Tables 15 and 16. Fatigue threshold strain levels are obtained from these curves (see Table 4). The bottom half of Figure 14 presents a photographic record of fatigue failures in the specimens corresponding to these test cases.

Tables 17 and 18 list the RTW compression fatigue test results for nonporous and porous specimens with partially loaded 3/16 in. diameter central holes. In every case, 10% of the total applied load was directly transferred to the fastener location. Figures 18 and 19 present corresponding plots of minimum cyclic strain versus cycles to failure. Fatigue threshold strain levels are obtained from these figures. Figures 20 and 21 present photographs of failed specimens corresponding to these fatigue test cases.

3.4 Summary of Results

A summary of test results from this program is presented in Table 4 and Figure 4, along with results from References 1 to 3 (see Section 1.2). It is assumed that the interaction among the discontinuities (drop-off of two 0° plies and a 3/16 in. diameter central hole at the ply drop-off location) and the induced defect (porosity) is represented by the following equation for RTW static compression tests:

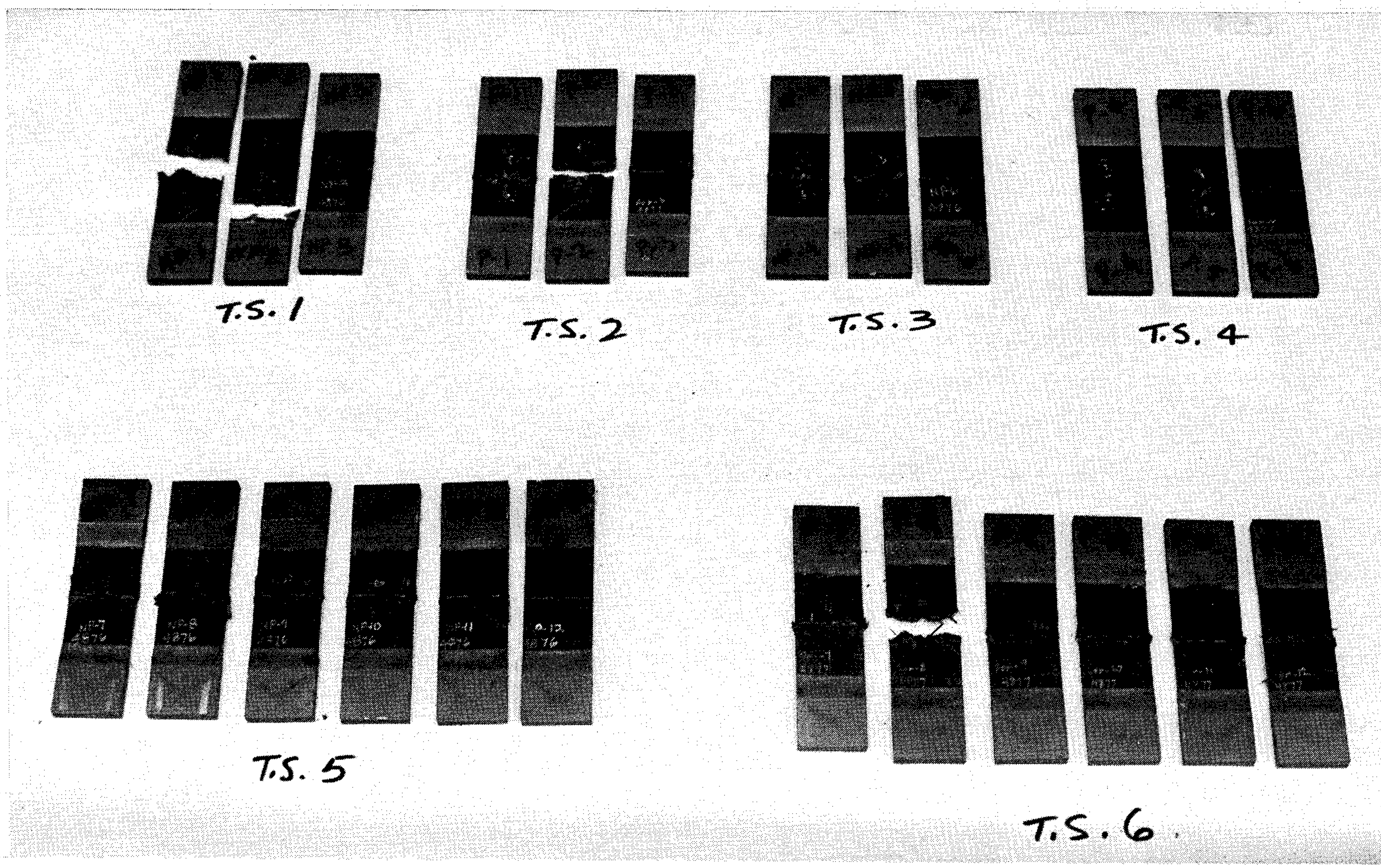


Figure 14. Failed Test Specimens Corresponding to Test Series 1 to 6 in Table 5.

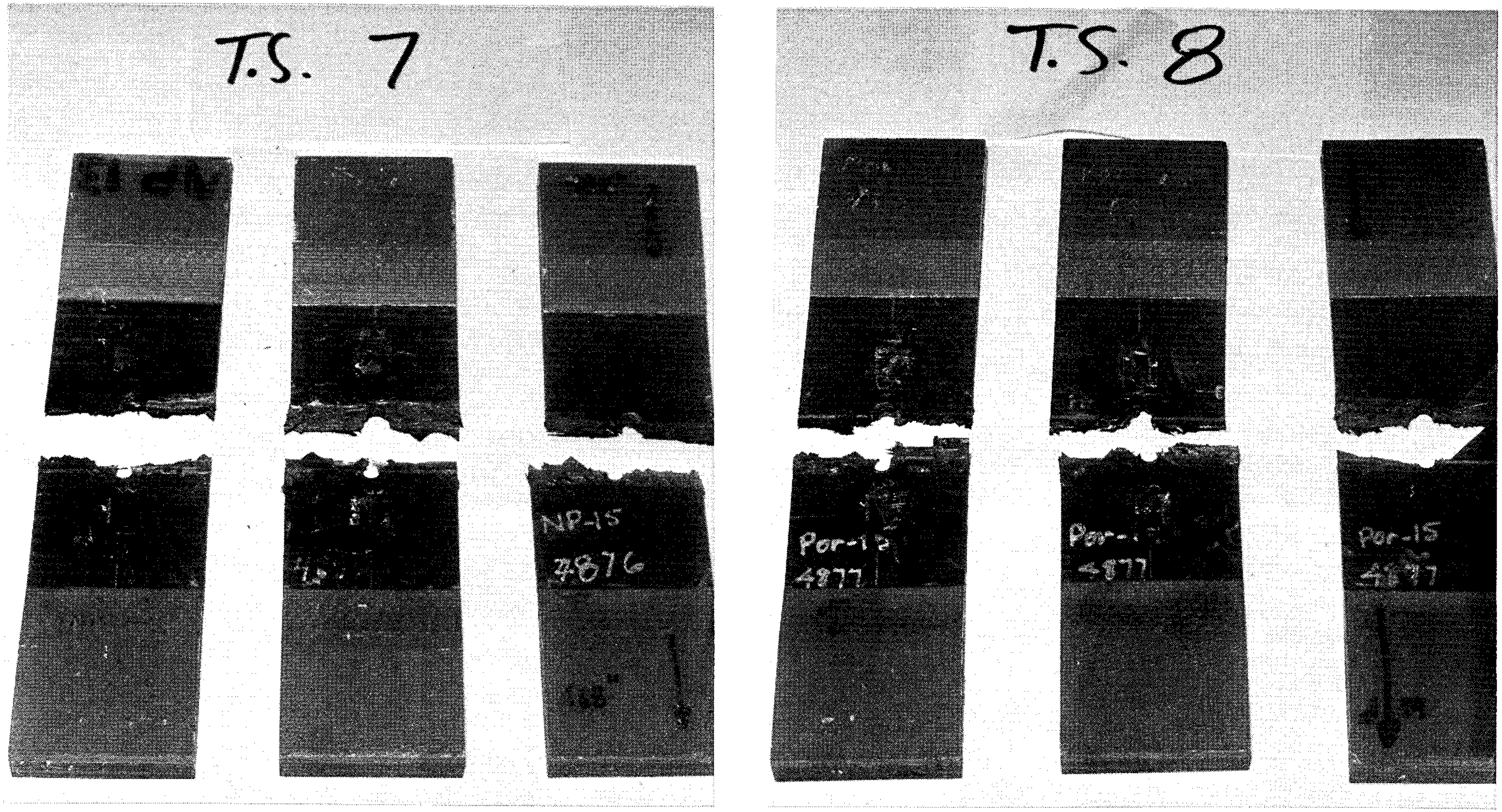


Figure 15. Failed Specimens Corresponding to Test Series 7 and 8 in Table 5.

TABLE 15. RTW FATIGUE TEST RESULTS ON NONPOROUS SPECIMENS WITH UNLOADED 3/16" DIAMETER CENTRAL HOLES+

Test Series	Specimen	P_{min} (kips)	$\sigma_{min}(30)$ (ksi)	$\sigma_{min}(28)$ (ksi)	$\varepsilon^*_{min}(30)$ (μin/in)	$\varepsilon^*_{min}(28)$ (μin/in)	$N_{failure}$ (cycles)
5	NP-7	-20.0	-54.469	-58.725	-4918	-5582	85,630
5	NP-8	-18.5	-49.840	-53.940	-4500	-5127	246,890
5	NP-9	-17.0	-45.973	-48.658	-4151	-4625	401,930
5	NP-10	-22.0	-59.302	-62.611	-5354	-5951	1020
5	NP-11	-19.0	-50.995	-54.791	-4604	-5208	148,740
5	NP-12	-16.0	-42.828	-45.901	-3867	-4363	1.30×10^6**

+ These constant amplitude fatigue tests were run at R=10 and ω=10 Hertz.

* Strains were computed using $E^c_x(30)$ = 11.076 Msi and $E^c_x(28)$ = 10.521 Msi (see Table 14)

** No failure (specimen run-out).

TABLE 16. RTW FATIGUE TEST RESULTS ON POROUS SPECIMENS WITH UNLOADED 3/16" DIAMETER CENTRAL HOLES+

Test Series	Specimen	P_{min} (kips)	$\sigma_{min}(30)$ (ksi)	$\sigma_{min}(28)$ (ksi)	$\varepsilon_{min}(30)$ (µin/in)	$\varepsilon_{min}(28)$ (µin/in)	$N_{failure}$ (cycles)
6	P-7	-18.5	-50.217	-53.283	-4755	-4987	140,260
6	P-8	-17.5	-47.554	-50.695	-4503	-4745	162,280
6	P-9	-15.0	-41.051	-43.757	-3887	-4096	2.367×10^{6}**
6	P-10	-20.0	-54.645	-58.824	-5174	-5506	31,240
6	P-11	-16.5	-44.691	-48.246	-4232	-4516	1,097,410
6	P-12	-19.5	-52.646	-56.228	-4985	-5263	36,460

+ These constant amplitude fatigue tests were run at R=10 and ω=10 Hertz.

* Strains were computed using $E_x^c(30) = 10.561$ Msi and $E_x^c(28) = 10.684$ Msi (see Table 14).

** No failure (specimen run-out)

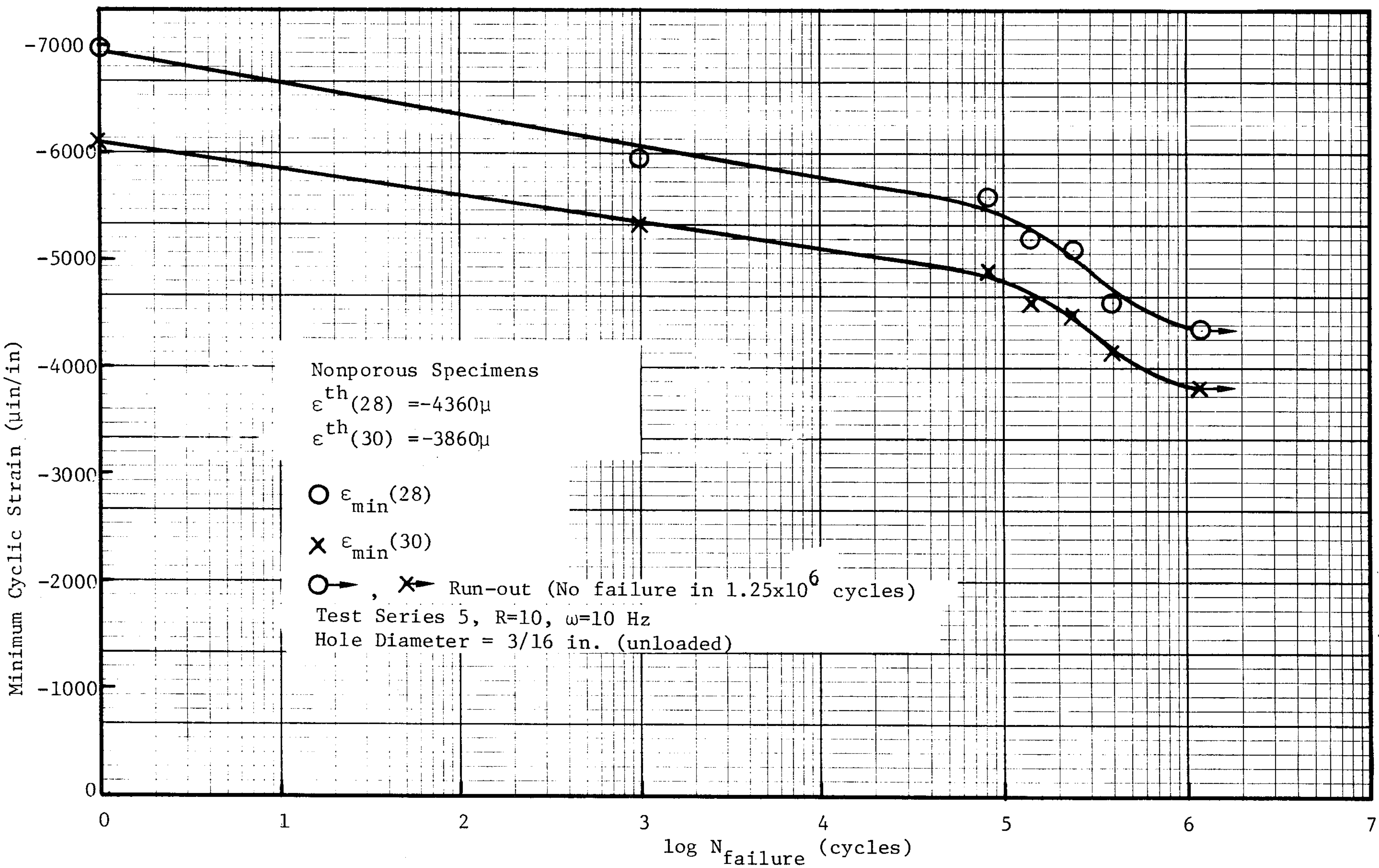


Figure 16. S-N Curves for Nonporous Specimens with Unloaded 3/16 in. Diameter Central Holes.

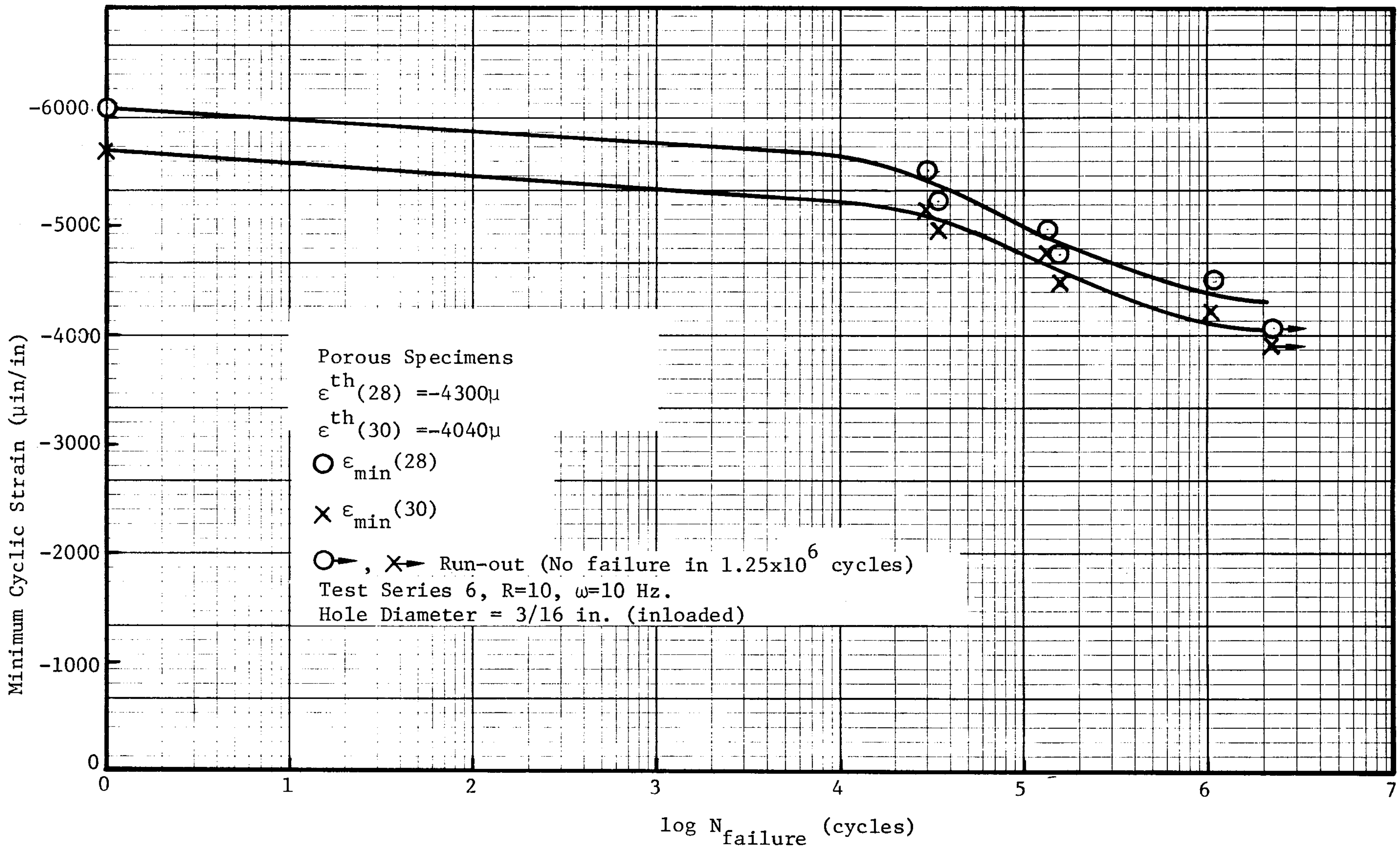


Figure 17. S-N Curves for Porous Specimens with Unloaded 3/16 in. Diameter Central Holes

TABLE 17. RTW FATIGUE TEST RESULTS ON NONPOROUS SPECIMENS WITH PARTIALLY LOADED 3/16" DIAMETER CENTRAL HOLES+

Test Series	Specimen	P_{min} (kips)	$\sigma_{min}(30)$ (ksi)	$\sigma_{min}(28)$ (ksi)	$\varepsilon_{min}(30)$* (μin/in)	$\varepsilon_{min}(28)$* (μin/in)	$N_{failure}$ (cycles)
9	NP-16	-22.0	-59.981	-64.145	-5141	-6094	55,220
9	NP-17	-20.0	-54.558	-58.212	-4676	-5530	164,600
9	NP-18	-18.0	-48.519	-52.421	-4159	-4980	1.0×10^6**
9	NP-19	-19.0	-51.521	-53.398	-4416	-5073	10,680
9	NP-20	-23.0	-63.469	-68.459	-5440	-6504	450
9	NP-21	-19.0	-51.132	-53.366	-4383	-5070	140,840

+ Tests were conducted at R=10 and ω=10 Hertz, with a bolt load/total total ratio of 0.1

* Strains were computed using $E_x^c(30) = 11.667$ Msi and $E_x^c(28) = 10.526$ Msi (see Table 14).

** No failure (specimen run-out)

TABLE 18. RTW FATIGUE TEST RESULTS ON POROUS SPECIMENS WITH PARTIALLY LOADED 3/16" DIAMETER CENTRAL HOLES+

Test Series	Specimen	P_{min} (kips)	$\sigma_{min}(30)$ (ksi)	$\sigma_{min}(28)$ (ksi)	$\varepsilon_{min}(30)$ (μin/in)	$\varepsilon_{min}(28)$ (μin/in)	$N_{failure}$ (cycles)
10	P-16	-22.0	-59.076	-64.437	-5587	-6202	1++
10	P-17	-20.0	-53.135	-57.737	-5025	-5558	940
10	P-18	-18.0	-48.544	-52.023	-4591	-5008	79,920
10	P-19	-17.0	-46.145	-48.963	-4364	-4713	178,040
10	P-20	-16.5	-45.230	-48.049	-4277	-4625	1.0×10^{6}**
10	P-21	-19.0	-51.630	-55.136	-4883	-5307	94,600

+ Tests were conducted at R=10 and ω=10 Hertz, with a bolt load/total load ratio of 0.1.

++ Failed at P_{min} = -22 kips when the initial strain survey (back-to-back gages) was conducted.

* Strains were computed using $E_x^c(30)$ = 10.574 Msi and $E_x^c(28)$ = 10.389 Msi (see Table 14).

** No failure (specimen run-out)

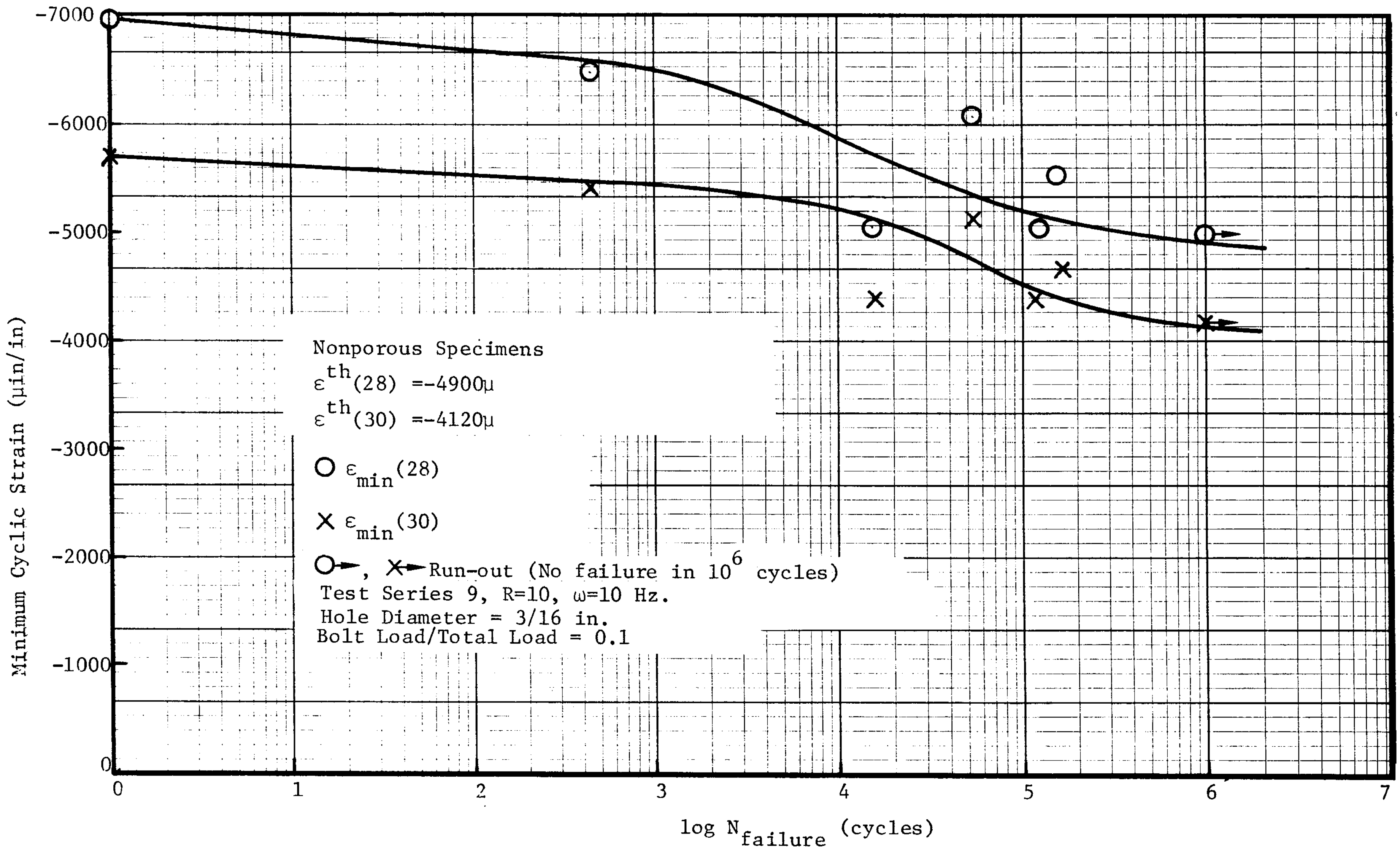


Figure 18. S-N Curves for Nonporous Specimens with Partially Loaded 3/16 in. Diameter Central Holes.

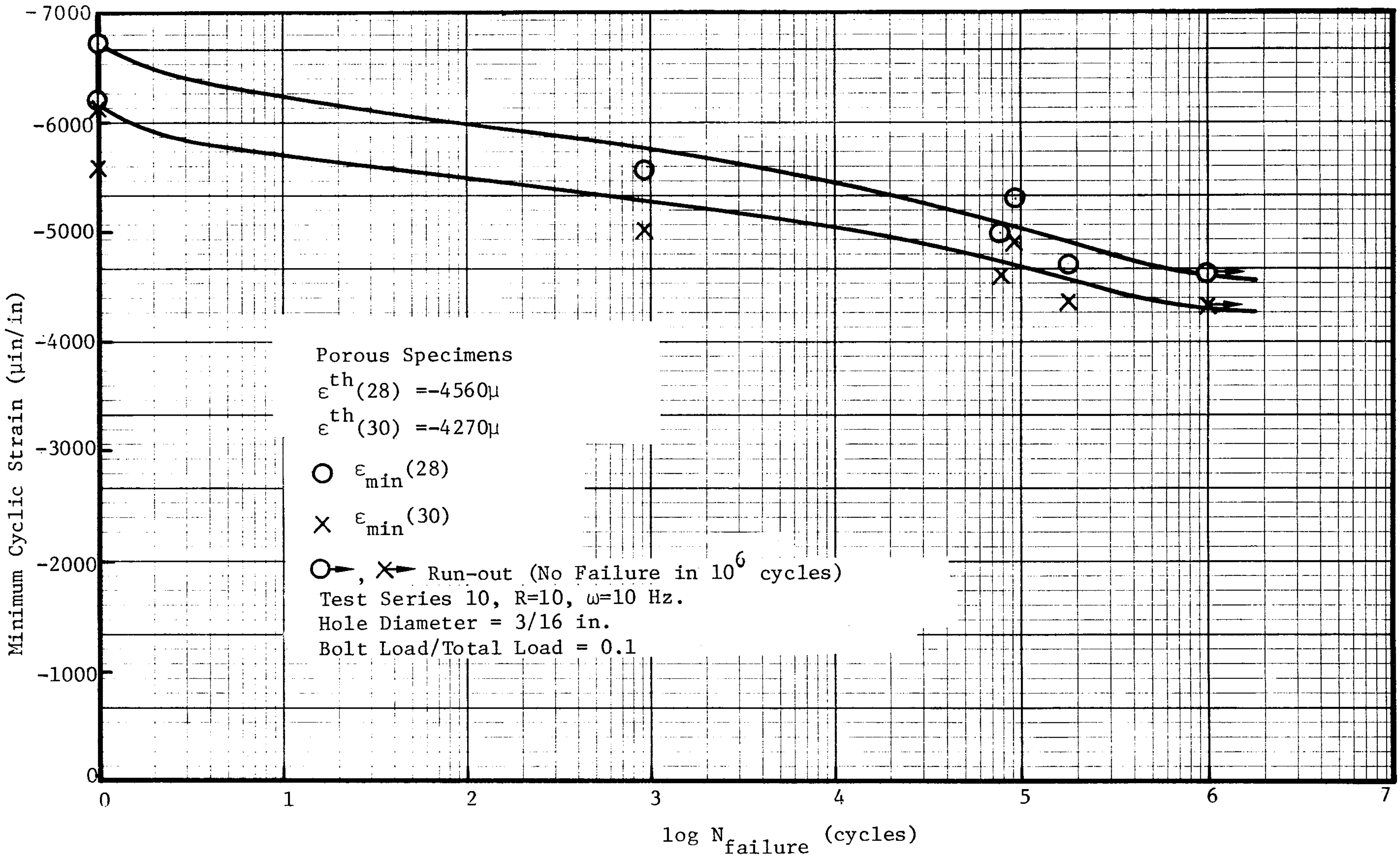


Figure 19. S-N Curves for Porous Specimens with Partially Loaded 3/16 in. Diameter Central Holes.

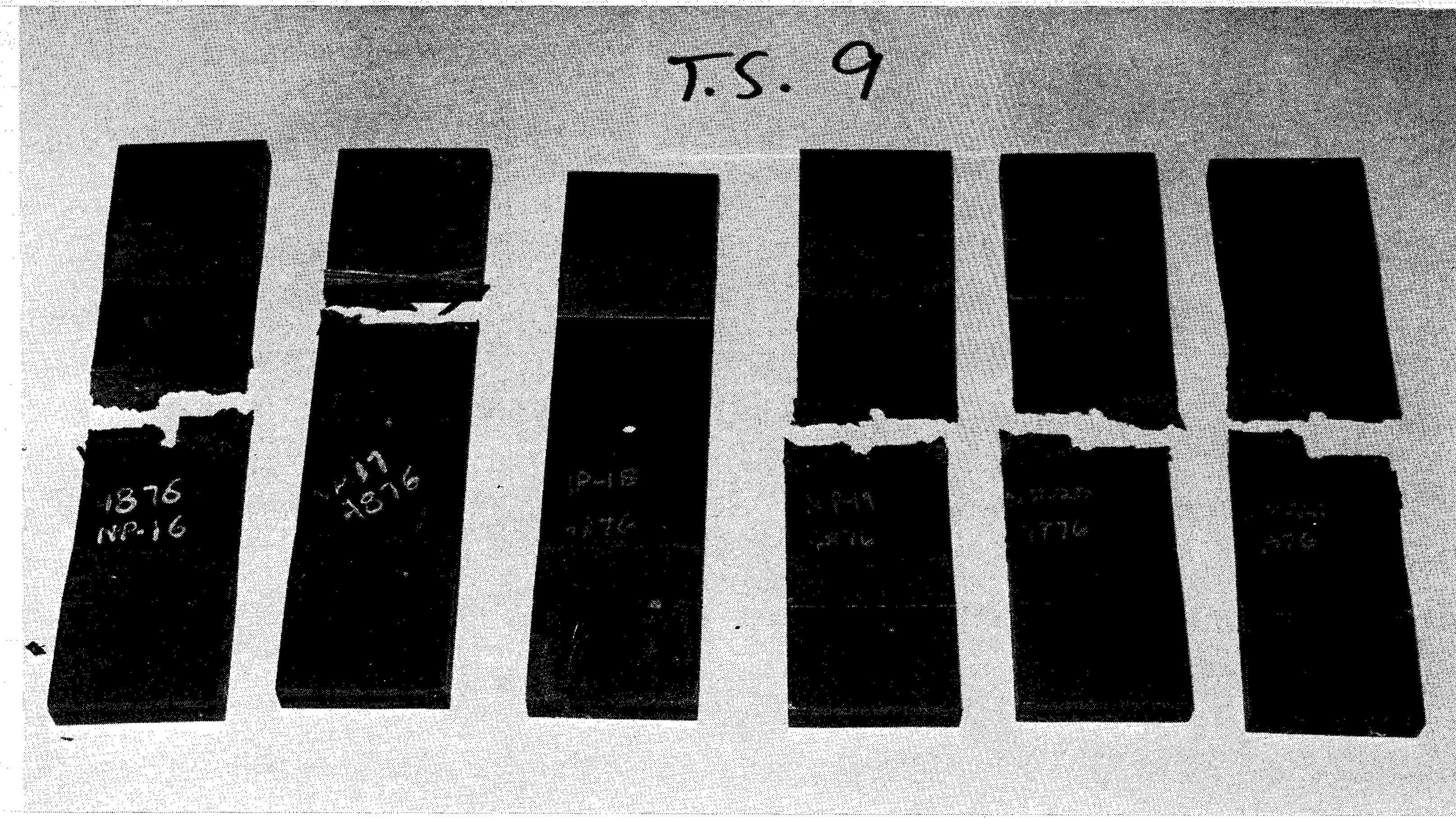


Figure 20. Failed Test Specimens Corresponding to Test Case 9.

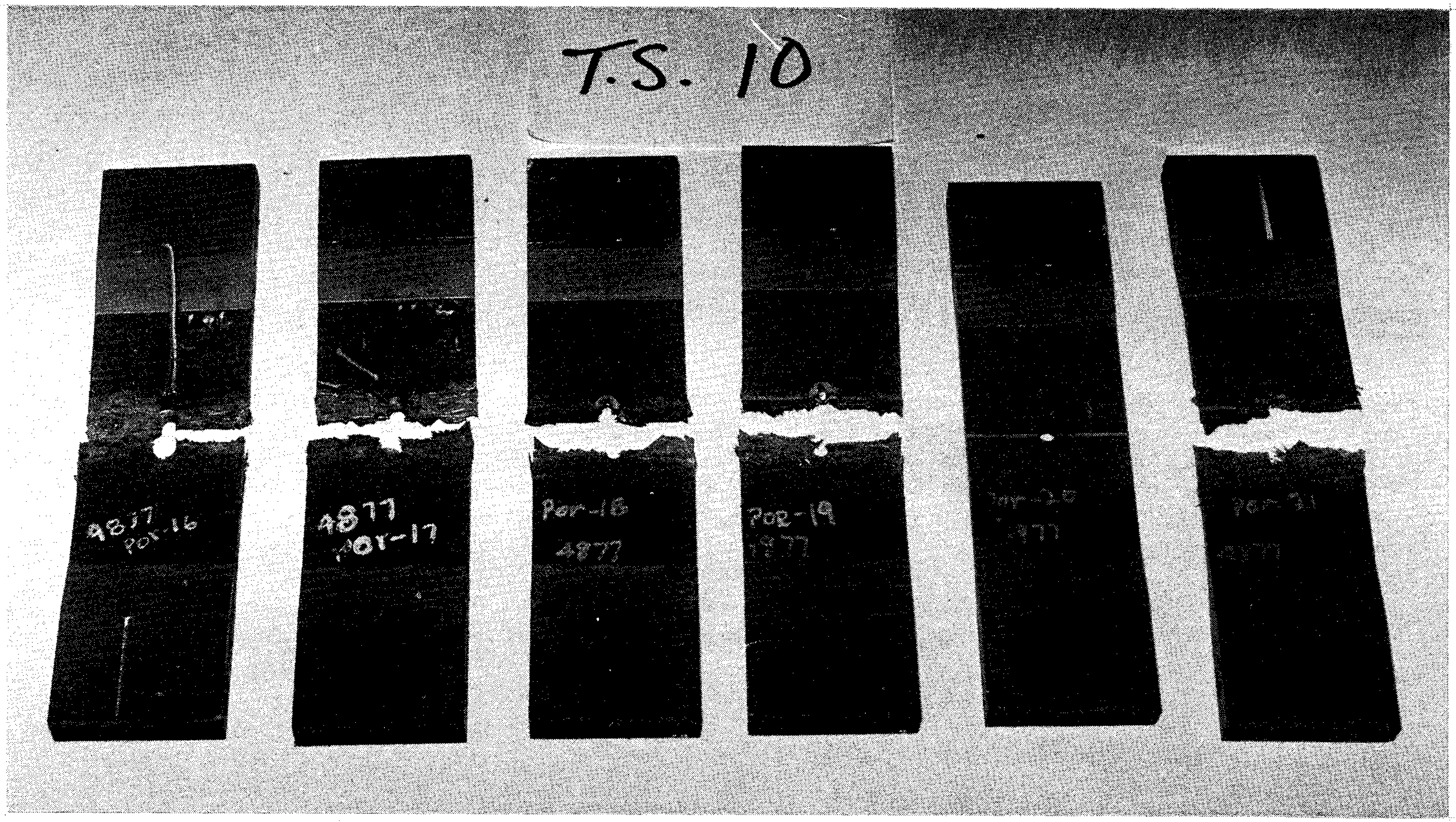


Figure 21. Failed Test Specimens Corresponding to Test Case 10.

$$\varepsilon^{cu}_{def/dis} = \varepsilon^{cu}_{no\ def/dis}\ (1-K_{def})\ (1-K_{dis})$$

where $\varepsilon^{cu}_{def/dis}$ and $\varepsilon^{cu}_{no\ def/dis}$ are the ultimate compressive strains with and without defects or discontinuities, respectively, and K_{def} and K_{dis} are the fractional losses in ε^{cu} due to defects and discontinuities, respectively. The results in Tables 4 and 14 yield:

$K_{porosity} = 0.0533$ and $K_{3/16''\ hole} = 0.4962$.

Therefore, $(1-K_{porosity})\ (1-K_{3/16''\ hole}) = 0.4769$. The measured ε^{cu} value for specimens with porosity and 3/16 in. diameter central holes is lower--0.4386 times the ε^{cu} value for specimens with no porosity or holes. The actual fractional loss in ultimate strain is therefore higher than that predicted by the assumed expression.

In Table 14, the results corresponding to porous, plain laminates with a ply drop-off reveal that, a 34.5% loss in ε^{cu} was recorded in one replicate (P-1), while only a 5.3% loss in ε^{cu} was recorded in the others. Since the residual strengths of specimens P-2 and P-3 were approximately the same, specimen P-1 was judged to have a level of porosity higher than the average value for the fabricated porous panel from which it was extracted. The actual loss in ε^{cu} for the porous specimens with a ply drop-off is expected to be approximately the value (14.4%) measured for the laminate without any ply drop-off (Table 4, Reference 3). Assuming $K_{porosity}$ to be 0.144, and retaining the $K_{3/16''\ hole}$ value of 0.4962, it is seen that:

$$\varepsilon^{cu}_{def/dis} = 0.4313\ \varepsilon^{cu}_{no\ def/dis}$$

This compares well with the measured value of 0.4386 $\varepsilon^{cu}_{no\ def/dis}$. It is noted here that there was no loss in ε^{cu} due to ply drop-off alone (see Table 4).

The results of this program, and those from the previous programs (References 1 to 3), find application in the quality assessment of manufactured laminated structural components. The current practice is to use records similar to the ones presented in Figure 22. The severity of porosity is assumed to be reflected by the dB attenuation (ΔdB) measured from a through-transmission ultrasonic inspection of the laminated component.

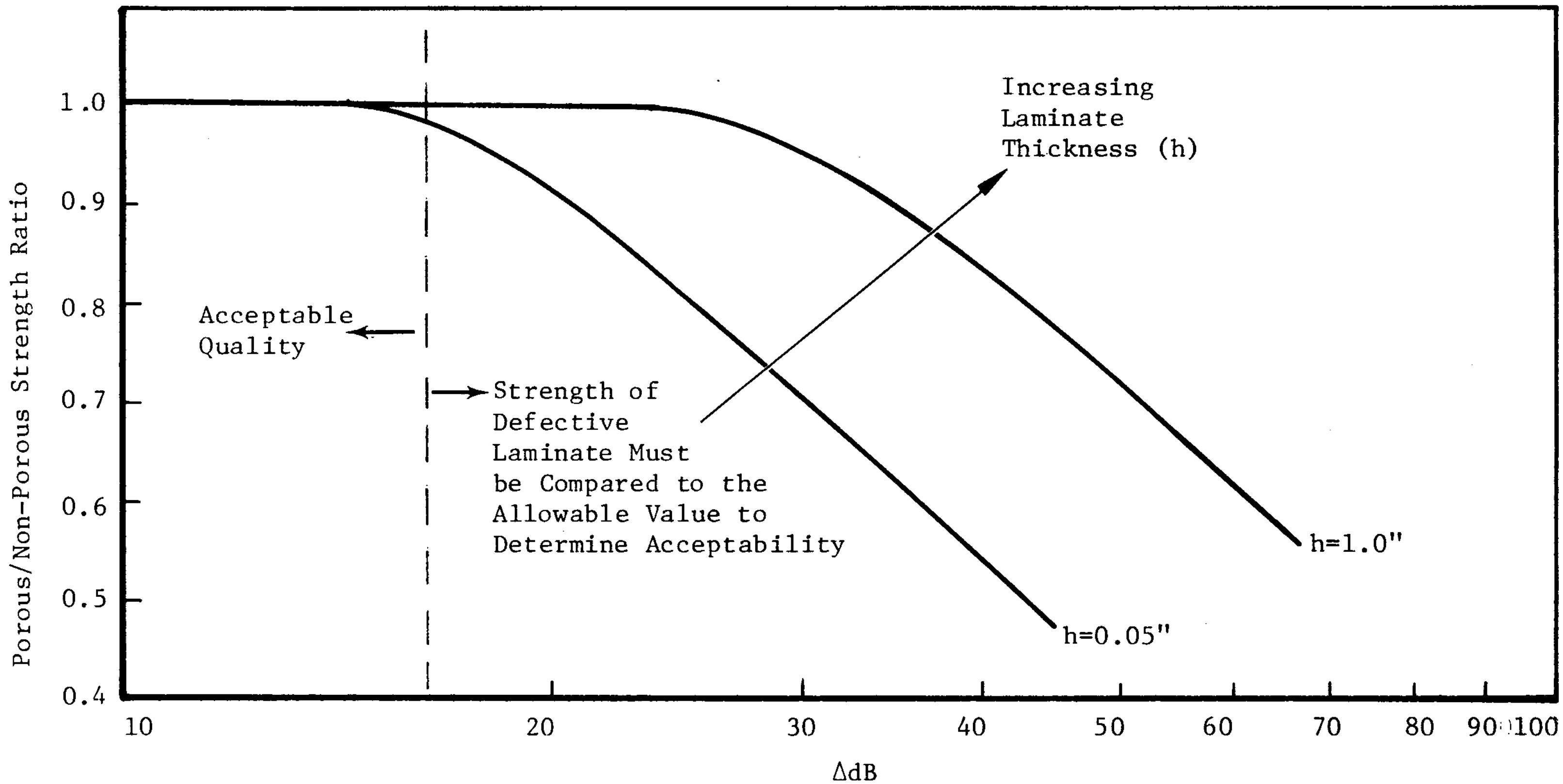


Figure 22. Typical Strength Loss Versus ΔdB Curves used in Determining Acceptability of Fabricated Laminates.

The input signal (dB) is increased until the transducer below the defective (porous) panel measures the dB value corresponding to a reference standard panel that is defect-free. The difference between the input signal and the transmitted signal is recorded as ΔdB. The reference dB value varies with the thickness of the inspected portion of the component. Tests on specimens with a wide range of porosity severity level (ΔdB) yield a relationship between porous-to-nonporous strength ratio and ΔdB for laminates of various thicknesses (See Figure 22). These tests may be the static compression tests conducted in the reported program, or other types of tests (short beam shear, flatwise tension, etc.--see References 4 to 6). Based on a family of curves similar to the ones in Figure 22, a ΔdB value may be picked, below which a negligible loss in laminate strength is induced by the corresponding porosity level. Thus an acceptance/rejection criterion may be established based on ΔdB measurements on the fabricated component, and utilized during the quality control nondestructive inspection (NDI) stage. Beyond the acceptable ΔdB level, the strength of the defective component (rejected by the quality control test) must be compared to the design allowable value. If the strength is above the design allowable value, the component may be accepted for service if the margin of safety is not very low. The acceptability of laminates that are rejected based on NDI records will be influenced significantly by the results of this program and those in References 1 to 6.

SECTION 4

CONCLUSIONS AND RECOMMENDATION

4.1 Conclusions

Static compression and constant amplitude compression fatigue (R=10, ω=10 Hz) tests were conducted on specimens which transitioned from a $[0_{16}/\pm45_5/90_4]_c$ layup to a $[0_{14}/\pm45_5/90_4]_c$ layup at midlength. Tests were conducted on defect-free specimens and specimens with 2.5 to 4.5% porosity by volume. Some specimens were tested in the fabricated form (with ply drop-off), and the others were tested after 3/16 in. diameter central holes were drilled at the ply drop-off location. In some specimens, 10% of the total applied load was introduced directly by a fastener at the hole location. Static compression tests provided ε^{cu} values and compression fatigue tests provided ε^{th} values (below which no fatigue failure occurs for over a million cycles at R=10 and ω=10 Hz).

The combined effects of discontinuities (ply drop-off and hole) and defects (porosity) were quantified by comparing program test results with those from References 1 to 3. A simple defect/discontinuity interaction formula was assumed and its validity was verified. The usefulness of the results generated in this program and in the earlier programs (References 1 to 3) was illustrated with the help of typical acceptance/rejection curves that are used during the NDI of fabricated laminated components.

4.2 Recommendation

Results in this report, and in References 1 to 3, address the compressive response of AS1/3501-6 graphite/epoxy laminates. These laminates are meant for 220^{0}F service applications, and are known to demonstrate poor tolerance to low velocity impact threats. New material systems are currently being investigated for higher service temperature applications and for improved damage tolerance -- bismaleimide matrix composites and thermoplastic matrix composites, respectively. It is recommended that the studies conducted in this report and in References 1 to 3 be repeated on these new materials to characterize their compressive behavior.

SECTION 5

REFERENCES

1. Grimes, G. C. and Adams, D. F., "Investigation of Compression Fatigue Properties of Advanced Composites", Northrop Technical Report NOR 79-17, Contracts N00019-77-C-0518 and N00019-77-C-0519 with the Naval Air Systems Command, October 1979.

2. Grimes, G. C., Adams, D. F., and Dusablon, E. G., "The Effects of Discontinuities on Compression Fatigue Properties of Advanced Composites", Northrop Technical Report NOR 80-158, Contracts N00019-79-C-0275 and N00019-79-C-0276 with the Naval Air Systems Command, October 1980.

3. Ramkumar, R. L., Grimes, G. C., Adams, D. F. and Dusablon, E. G., "Effects of Materials and Processes Defects on the Compression Properties of Advanced Composites", Northrop Technical Report NOR 82-103, Contracts N00019-80-C-0484 and N00019-80-C-0490 with the Naval Air Systems Command, May 1982.

4. Knauss, J. F., and Black, G. T., "The Effect of Porosity on the F/A-18A Vertical Tail Skin", Northrop Report NOR 81-315, September 1981.

5. Ramkumar, R. L., "Effect of Porosity on the Flatwise Tensile Behavior of AS/3501-6 Graphite/Epoxy Laminates", Northrop Report No. NOR 82-43, February 1982.

6. Bohlmann, R. E., et al., "Development of Acceptance Criteria for Graphite/Epoxy Structure", Contract N00019-76-C-0666, Amendment A00209, Report No. MDC A7361, September 1981.

APPENDIX A

- PREPREG QC REQUIREMENTS
- QUALITY ASSURANCE CERTIFICATION DATA
- FABRICATION WORK ORDER
- TEST WORK ORDER

PREPREG REQUIREMENTS FOR HERCULES AS/3501-6 GRAPHITE/EPOXY

Incoming graphite/epoxy prepreg shall conform to the requirements as set forth in MMS-549. In case of conflict between this document and MMS-549, the requirements of this document shall take precedence. Acceptance testing shall be performed at Northrop to verify these requirements and in accordance with MCAIR P.S. 21332. In case of conflict, this document will take precedence.

AS/3501-6 ACCEPTANCE REQUIREMENTS

PROPERTY	ACCEPTANCE REQUIREMENTS*		TEST METHOD
	TYPE I	TYPE II	
Nongraphite content (%W)	42 ± 3	35 ±3	P.S. 21332
Flow (%)	12 to 30	15 to 30	P.S. 21332
Volatile content, 250F (%W)	1.5 maximum	1.5 maximum	P.S. 21332
0° flexural strength, ksi	220 min avg	220 min avg	IT-58 Para. 3.14
Laminate fiber volume (%V)	62 ±3	62 ±3	IT-58 Para. 3.14
Laminate void content (%V)	1 maximum	1 maximum	IT-58 Para. 3.14
Laminate specific gravity	1.59 to 1.63	1.59 to 1.63	IT-58 Para. 3.15
Transverse tension (μ-in/in)	5,000 min avg 4,000 min individual	5,000 min avg 4,000 min individual	IT-58** IT-58**

Laminates to be cured per instructions in Process Instruction Sheet M&P-D No. 1.

Material that has been stored more than six months at 0°F, or has been exposed to room temperature for more than a cumulative total of 40 hrs, must be retested prior to use.

*Based on a minimum of three determinations. Type I single ply; Type II double ply.

**Clip-on extensometer may be used for strain measurements.

QUALITY ASSURANCE CERTIFICATION

CUSTOMER: Northrop

PURCHASE ORDER NO: 172-047455-002

MATERIALS: Graphite Fiber/Epoxy Material, 3501-6/AS1, 60" broadgoods

SPECIFICATION: MMS 549, Rev. B, Type I

QUANTITY: 971.00 lbs.

LOT NO: 60052099 Manufactured February 8, 1982

SPOOL NO: 5 & 10

RESIN LOT NO: 157 Manufactured by Hercules Inc.

FIBER LOT NO: 008-2A Manufactured by Hercules Inc.

I. Fiber Properties

	Spec Req	Lot Average
Tensile Str., ksi	410 minimum	516
Tensile Mod., msi	32 - 36	34
Density, lb/in^3	0.0640-0.0660	0.0654
Specific Gravity	1.7715-1.8269	1.8103

II. Prepreg Physical Properties

	Resin Flow	Volatiles	Tack
	Spec Req	Spec Req	Spec Req
	10 - 25,%	1.5% maximum	Table I, spec
Spool No.		Average/Individual	
5	17	1.1/1.0,1.2,1.0	Conforms
10	18	0.7/0.9,0.7,0.5	Conforms

III. Laminate Mechanical Properties

	Spec Req (min ind)	Panel No.	Average/Individual
		Spool 5	
0° Tensile Str., RT, ksi*	200	15931	264/266,254,271
0° Tensile Mod., RT, msi*	18.0	15931	20.[illegible]0.6,21.0,20.0
0° Elongation, RT, μ in/in x 10^3	10.0	15931	12.9/12.9,12.2,13.5
Short Beam Shear, RT, ksi	15.0	15932	19.4/20.2,19.5,18.5
Short Beam Shear, 250°F, ksi	9.0	15932	14.3/14.3,14.2,14.3
Short Beam Shear, 250°F, ksi (24 hour H_2O boil)	7.5	15932	11.0/10.9,11.1,11.2
		Spool 10	
0° Tensile Str., RT, ksi*	200	16008	283/252,292,306
0° Tensile Mod., RT, msi*	18.0	16008	21.2/20.6,21.6,21.5
0° Elongation, RT, μ in/in x 10^3	10.0	16008	13.3/12.0,13.7,14.3
Short Beam Shear, RT, ksi	15.0	16009	20.4/20.4,20.6,20.2
Short Beam Shear, 250°F, ksi	9.0	16009	14.7/14.6,14.7,14.7
Short Beam Shear, 250°F, ksi (24 hour H_2O boil)	7.5	16009	11.4/11.3,11.5,11.5

* Normalized to 0.0416 Panel Thickness.

QUALITY ASSURANCE CERTIFICATION
Page 2
Lot No: 60052099
March 16, 1982

IV. Panel Physical Properties

	Spec Req		
Spool No./Panel No.		5/15931	10/16008
Ply Thickness, Inches	0.0052 +/- 0.0003	0.0054	0.0053

V. Individual Spool Physical Properties

	Resin Content,%	Fiber Areal Wt.,gm/m^2
Spec Req	42 +/- 3 (Ind.)	145 155 (Ind.)
Spool No.	Average/Individual	Average/Individual
5	41/41,41,41	152/151,151,153
10	41/41,41,41	154/155,154,154

J. A. Rasmussen
J. A. Rasmussen, Plant 3
QUALITY CONTROL

JAR:mh

FABRICATION WORK ORDER NO. 1 To ORGN. 3876, 3874

SUBTASK: Comp. Prop. of Porous Lam. in the Presence of PDO & Fast. Holes

SALES ORDER 30959 **WPA** ____________

PREPARED BY: R. L. Ramkumar

APPROVED BY: Ramkumar **DATE** Aug. 2, 1982

SPECIAL INSTRUCTIONS & SPECIMEN DESCRIPTION:

Orgn. 3876:

(1) Fabricate one non-porous laminate per Figure A1. The material shall be Type I AS/3501-6 graphite/epoxy prepreg. The laminate should have a 30-ply layup in the central portion, marked "C" in Figure 1. The top and bottom quarters should have a 28-ply layup, marked "C1" in Figure A1. The 30-ply and 28-ply layups are shown in Figure A2. The ply drop-off locations are shown in Figure A1 by dashed lines.

(2) Layup Procedure for Non-Porous Laminates:

1. Cut, layup, and debulk books of material as necessary.
2. Over a clean caul plate covered with nonporous Armalon, layup the graphite prepreg books precut to the size, stacking order, and number of plies, as specified in the appropriate drawing or specification. Use cork, coreprene, or silicone rubber dams around circumference.
3. A ply of porous Armalon shall be placed over the graphite prepreg followed by plies of 120 glass bleeder cloth. A ratio of one ply of 120 glass cloth to four plies of graphite shall be used.
4. One ply of nonporous Armalon shall be placed on top of the last ply of 120 glass bleeder cloth.
5. Wrap the assembly with a minimum of three layers of Osnaburg cloth.

(3) Cure Cycle for Non-Porous Laminate

1. Apply full vacuum (24-inch to 28-inch Hg) to the bagged assembly and apply 85 ± 5 psig autoclave pressure.
2. Heat to 240 ± 10F at a heatup rate of 3F/min to 6F/min, hold at 240F to 60 to 70 minutes.

3. Increase autoclave pressure to 100 psig and vent vacuum bag, heat to 350F at a rate of 1F/min to 6F/min.

4. Hold at 350F for two hours (120 $\pm$10 minutes).

5. Cool the assembly to 150F or less under pressure.

6. Release the pressure and then remove assembly from autoclave.

7. Postcure the assembly at 350F for a minimum of 8 hours in an air-circulating oven.

(4) Fabricate <u>one porous</u> laminate per Figure 1. The material shall be the same (Type I AS/3501-6 graphite/epoxy). The laminate has the same layup/ply drop-off as the non-porous laminate (Figs. 1, 2 & Table 1).

(5) <u>Layup procedure for porous laminate</u>:

1. Cut, layup, and debulk books of material as necessary.

2. Over a clean caul plate covered with nonporous Armalon, layup the graphite prepreg books precut to the size, stacking order and number of plies as specified in the appropriate drawing or specified in the appropriate drawing or specification. Use cork, coreprene, or silicone rubber dams around circumference.

3. A ply of porous Armalon shall be placed over the graphite prepreg followed by plies of 120 glass bleeder cloth. A ratio of one ply of 120 glass cloth to the required amount of graphite shall be used.

4. One ply of nonporous Armalon shall be placed on top of the last ply of 120 glass bleeder cloth.

5. Wrap the assembly with a minimum of three layers of Osnaburg cloth.

6. Vacuum bag the entire assembly.

(6) <u>Cure Cycle for Porous Laminate</u>:

1. Apply full vacuum (24-inch to 28-inch Hg) to the bagged assembly and apply 15$\pm$2 psig autoclave pressure.

2. Heat to 240$\pm$10 F at a heat-up rate of 3°F/min to 6°F/min, hold at 240°F for 60 to 70 minutes.

3. Holding autoclave pressure at 15 psig, vent bag and raise temperature to 350°F at 1 to 6°F/min.

4. Hold at 250°F for two hours (120 $\pm$10 minutes).

5. Cool the assembly to 150°F or less under pressure.

6. Release the pressure and then remove assembly from autoclave.

7. Postcure the assembly at 350^{0}F for a minimum of 8 hours in an air-circulating oven.

(7) Fabricated panels (P and NP) shall be inspected via ultrasonic through transmission (C-scan) to determine their quality.

(8) Inspected panels shall be delivered to the machine shop (Orgn. 3874), labelled "P" & "NP".

Orgn. 3874:

(9) Block machine panels "P" & "NP", after trimming a 1" border, and the inner 1" strip for void content measurements.

(10) Extract QC specimens identified as V1 to V4, LC1 to LC4, TC1 to TC4, F1 to F4, and M1 to M8, from each laminate. Identify specimens from the "NP" laminate as:

NP-V1, NP-LC-2, NP-F4, NP-M3, etc.

and the specimens from the "P" laminate as:

P-V1, P-V2, P-LC1, P-F1, P-M2, etc.

(11) Deliver block-machined "P" and "NP" panels to orgn. 3876 for block-tabbing.

Deliver QC specimens to Ramkumar, Orgn. 3852/82

Orgn. 3876:

(12) Tab the block-machined panels as shown in Figure A3. A 15-ply, glass/epoxy laminate ($[0]_{15}$) shall be bonded to the blocks using AF 143 adhesive.

(13) Deliver block-tabbed panels to orgn. 3874 for specimen extraction.

Orgn 3874:

(14) Obtain 8" x 2" test specimens from the block-tabbed panels. The test specimen geometry is shown in Figure A3. Specimen ends shall be ground to be flat and parallel for compression testing.

(15) In 20 specimens from each laminate (NP and P), drill a hole at the center. The hole diameter shall be 3/16"; permissible hole diameter tolerances are + 0.003", - 0.0".

(16) Please notify Ramkumar (X5075) when specimens are ready for testing. Identify specimens appropriately, like NP-1, NP-2, NP-3, P-1, P-2, P-23.

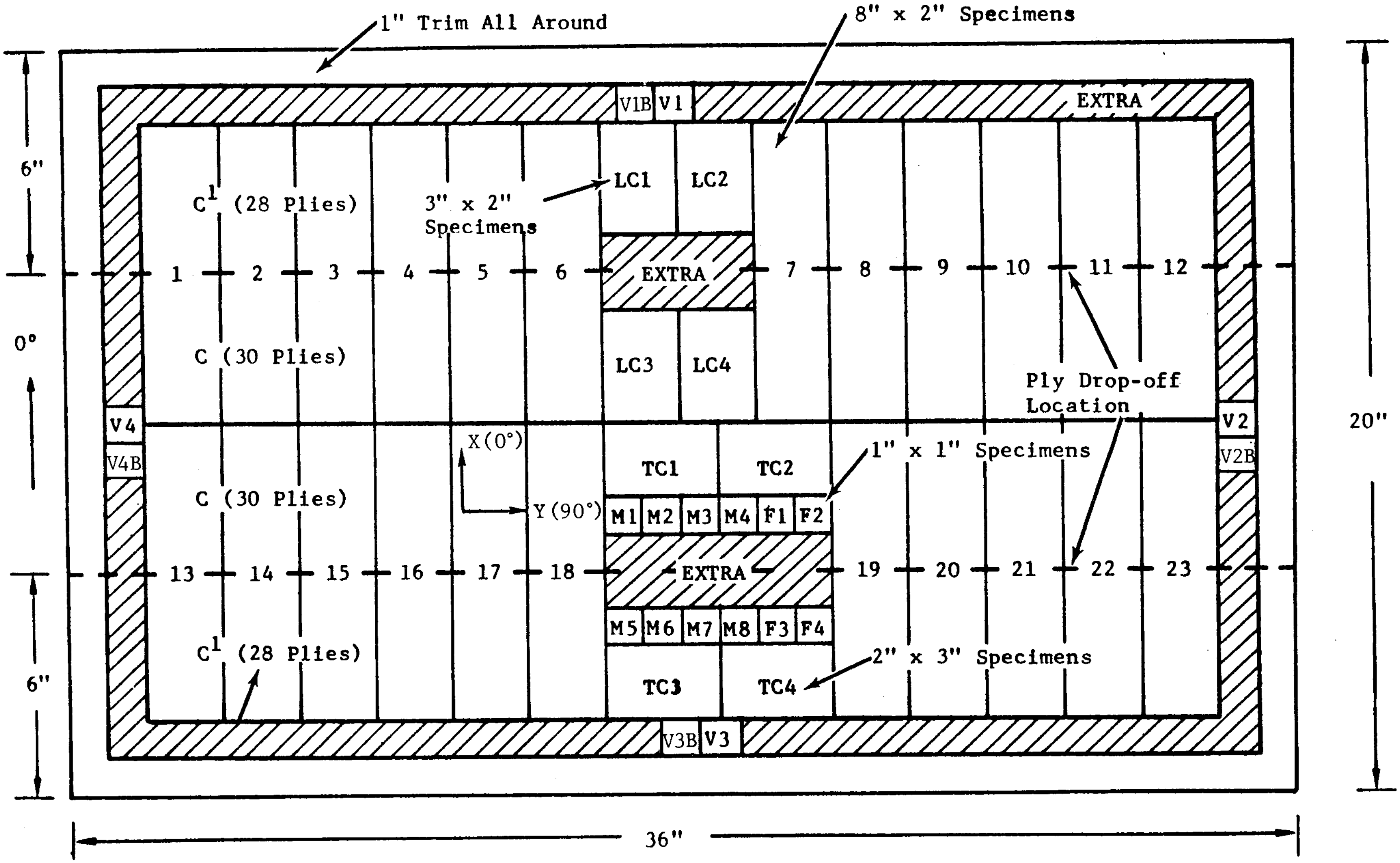


Figure A1. Geometry of Test Laminates NP and P.

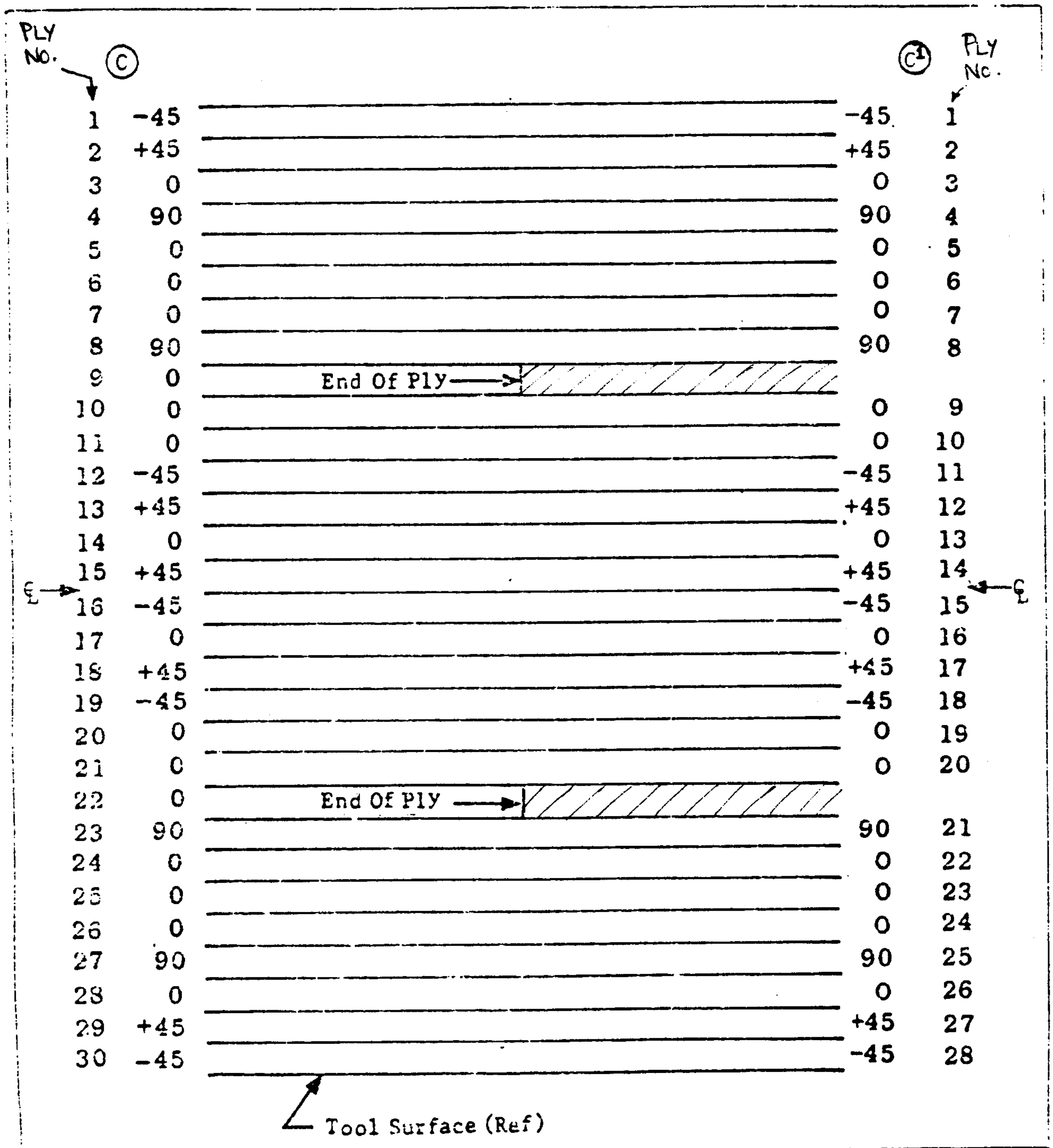
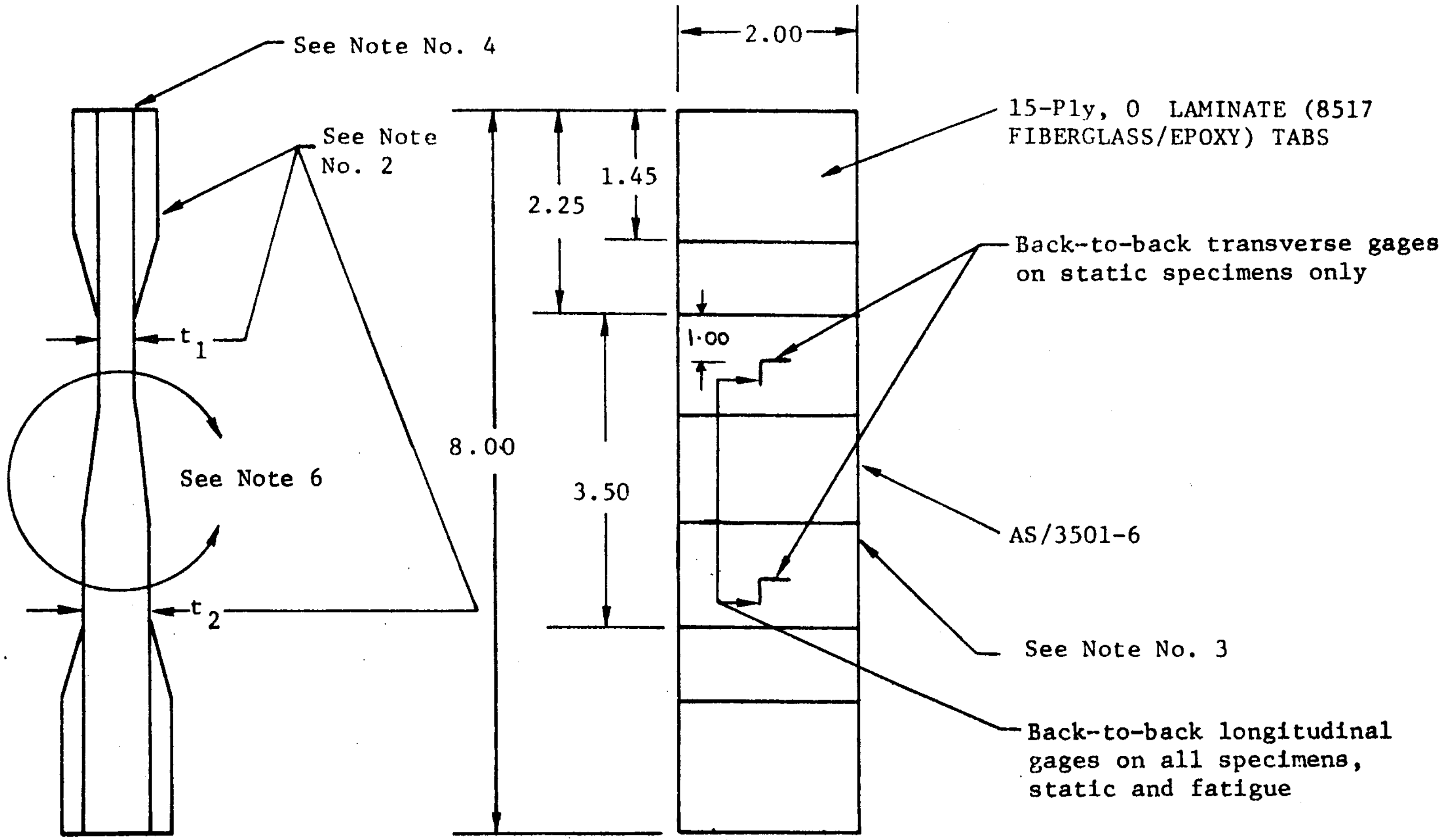


Figure A2. Details of Ply Drop-Off.



1. BOND 8517 TABS WITH AF-143 ADHESIVE.
2. SPECIMEN THICKNESS SHALL NOT VARY MORE THAN ± 0.005 INCH FROM NOMINAL.
3. SPECIMEN LONGITUDINAL EDGES SHALL BE PARALLEL TO 0.005 INCH.
4. TOP END AND BOTTOM END SURFACES SHALL BE FLAT AND PARALLEL TO 0.001 INCH.
5. USE "ATMUR" STATIC AND FATIGUE TEST FIXTURES AS REQUIRED.
6. SEE FIGURES 1 AND 2 FOR DETAILS.

Figure A3. Test Specimen Geometry.

TEST WORK ORDER NO. 1 | To ORGN. 3183

SUBTASK: Comp. Prop. of Porous Lams. In the Presence of PDO & Fast. Hole

SALES ORDER 30959 **WPA** ______

PREPARED BY: R. L. Ramkumar

APPROVED BY: Ramkumar **DATE** August 2, 1982

SPECIAL INSTRUCTIONS & SPECIMEN DESCRIPTION:

(1) Conduct static compression tests on QC specimens in the fixture shown in Figure A4. QC specimens to be tested under RTD conditions are:

NP-LC1 to NP-LC4, NP-TC1 to NP-TC4
P-LC1 to P-LC4, P-TC1 to P-TC4.

A total of 16 QC specimens (3 " x 2") shall be tested under RTD conditions. Dry the specimens prior to testing, under 170°F conditions for a few hours, and obtain their measurements (width and thickness). (No Strain Gaging)

(2) Notify Ramkumar (X5075) when QC tests are completed. QC properties should conform to requirements listed in Tables A1 and A2.

(3) Test specimens for the main program have the geometry shown in Figure A3. 42 specimens (plus 4 extra specimens) will be tested in accordance with Table A3. All tests will be under room temperature wet (RTW) conditions.

(4) Dry the (46) test specimens in an oven (170°F) for a few hours (overnight), along with the 16 traveler coupons (NP-M1 to NP-M8, and P-M1 to P-M8). The moisture travellers are 1" x 1" in dimensions. Seal the edges of the travelers, and the edges, hole boundaries and tab regions of test specimens, after drying them. Weigh the travelers, before and after sealing the dry edges.

(5) Introduce the test specimens and travelers into an oven, and subject them to the following exposure:

63 days at 170°F and 95% RH, plus
36 days at 170°F and 80% RH.

Monitor the traveler weights every week.

(6) At the end of moisture conditioning, present weight data to Ramkumar. If the data are acceptable, seal the wet specimens in aluminum foil bags, separating them by test series:

Test Series	Specimen ID	Test Series	Specimen ID
1	NP-1, 2, 3	6	P-7, 8, 9, 10, 11, 12
2	P-1, 2, 3	7	NP-13, 14, 15
3	NP-4, 5, 6	8	P-13, 14, 15
4	P-4, 5, 6	9	NP-16, 17, 18, 19, 20, 21
5	NP-7, 8, 9, 10, 11, 12	10	P-16, 17, 18, 19, 20, 21

(7) AFTER moisture conditioning, mount back-to-back longitudinal and transverse strain gages on the following specimens (8 gages each):

NP-1, P-1, NP-4, P-4, NP-13, P-13
NP-2, P-2, NP-5, P-5, NP-14, P-14

Strain gages shall be positioned as shown in Figure A3. Use 350 ohm gages with a type 03 (micromeasurements designation) compatible backing.

(8) Also mount, AFTER moisture conditioning, back-to-back longitudinal gages, only on the thinner portion of the following specimens:

NP-7, NP-8, P-7, P-8
NP-16, NP-17, P-16, P-17 (2 gages each)

(9) Tests corresponding to test series 1 to 4 will be conducted in the ETL (Atmur) test fixture with platen side supports.

(10) Report static test data to Ramkumar (3852/82) before starting tests for test series 5 and 6.

(11) Tests for test series 5 & 6 will be conducted in the ETL/Atmur test fixture with roller constraints. Ramkumar will provide the maximum cyclic load values based on static test data. Use the back-to-back longitudinal gages to ensure load alignment. Constant amplitude fatigue tests will be compression-compression fatigue tests with an R RATIO (minimum/maximum cyclic load ratio) of 10, and will be conducted at a frequency of 10 Hertz. If a specimen survives 1.25×10^6 cycles of the applied loading (without failing) it will be labelled to have "run-out".

(12) Tests corresponding to test series 7 to 10 will be conducted in the setup shown in Figure A3. Ramkumar will prescribe the ratio of the bolt load to the total load, prior to initiating these tests. Conduct series 7 & 8, report test data to Ramkumar, obtain cyclic load amplitudes from him for series 9 & 10, and use back-to-back gages to check load alignment.

(13) For test series 7 to 10, use a 3/16" diameter titanium bolt at the hole (ST3M 782-3-4 shear head Jo-bolt).

(14) Provide photographs of test setups & failed specimens as requested by Ramkumar.

All dimensions in inches (1 in. = 25.4 mm)

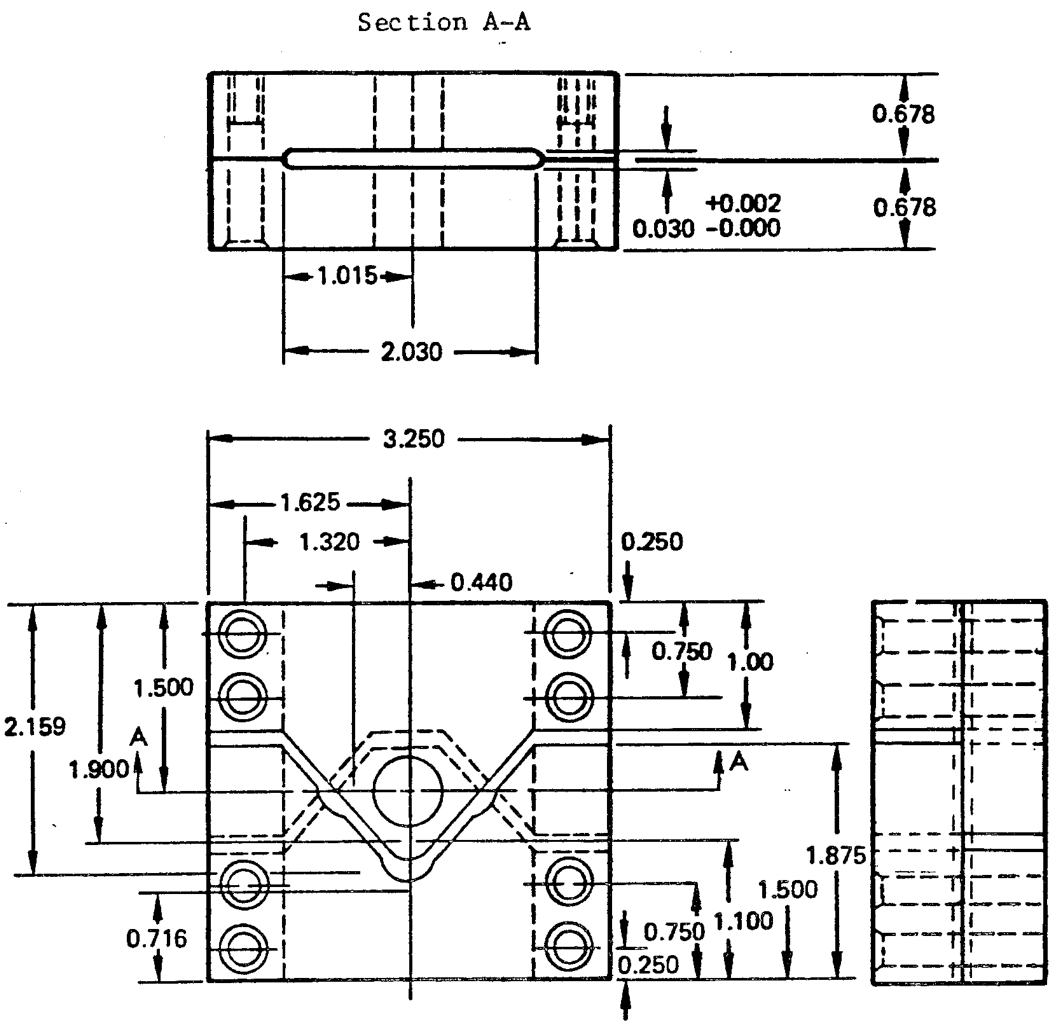


Figure A4. Static Compression Test Fixture.

TABLE A1. PHYSICAL AND MECHANICAL PROPERTY REQUIREMENTS FOR P LAMINATE.

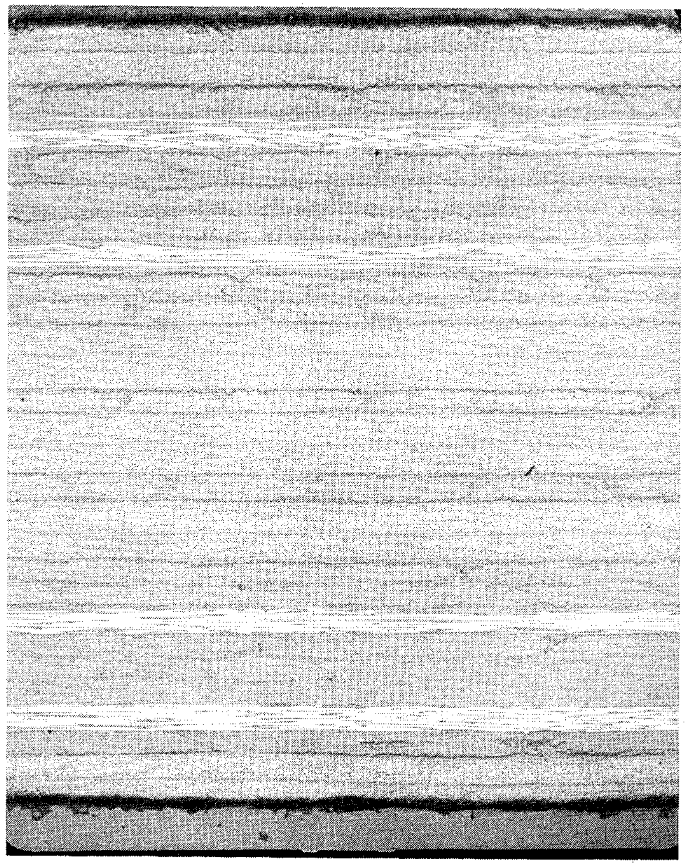
PROPERTY	ACCEPTABLE REQUIREMENTS	TEST METHODS
Fiber volume	55±5 percent	IT-58, para. 3.14
Void Content	3% ± 2	IT-58, para. 3.14
Specific gravity	1.45 to 1.55	IT-58, para. 3.15
Transverse compression:		
a) $[90]_{nc}$	25 ksi	See Figure 1
b) ±45/0/90	40 ski	See Figure 1
Longitudinal compression strength minimum, individual: a) $[0]_{NC}$	110 ksi	See Figure 1
b) ±45/0/90	90 ksi	See Figure 1
Transverse Tension: ±45/0/90	25 ksi	ASTM D-3039

TABLE A2. PHYSICAL AND MECHANICAL PROPERTY REQUIREMENTS FOR NP LAMINATE.

PROPERTY	ACCEPTABLE REQUIREMENTS	TEST METHODS
Fiber volume	59 ±4 percent	IT-58, para. 3.14
Void Content	≤ 1 percent	IT-58, para. 3.14
Specific gravity	1.56 to 1.62	IT-58, para. 3.15
Transverse compression:		
a) $[90]_{nc}$	30 ksi	See Figure 1
b) ±45/0/90	50 ksi	See Figure 1
Longitudinal compression strength minimum, individual: a) $[0]_{NC}$	120 ksi	See Figure 1
b) ±45/0/90	94 ksi	See Figure 1
Transverse Tension: ±45/0/90	30 ksi	ASTM D-3039

APPENDIX B

- PHOTOMICROGRAPHS OF NONPOROUS AND POROUS PANEL SECTIONS.
- SAMPLE POROSITY CALCULATION USING CHEMICAL ANALYSIS MEASUREMENTS.
- MOISTURE DATA ON POROUS AND NONPOROUS TRAVELERS.

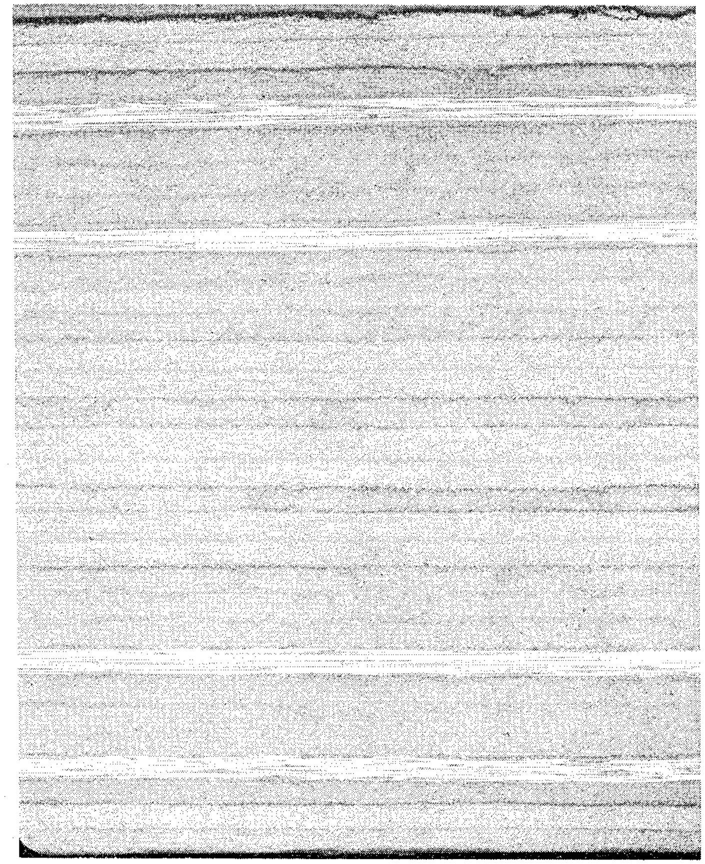


NPV1B

NPV2B

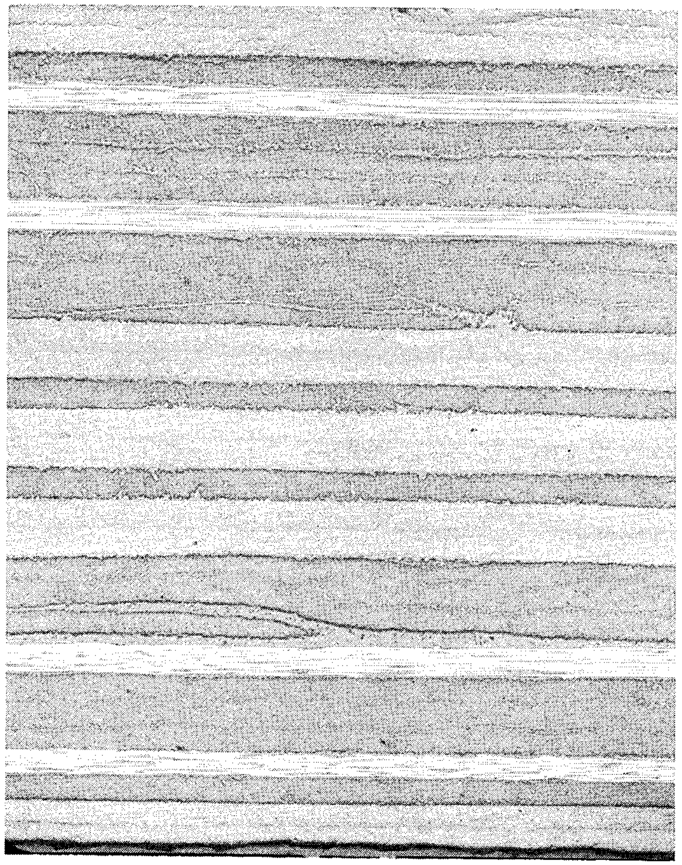
Figure B1. Photomicrographs (25X) of YZ Cross-Sections of the Non-Porous Laminate (see Figure 2).

NPV3B

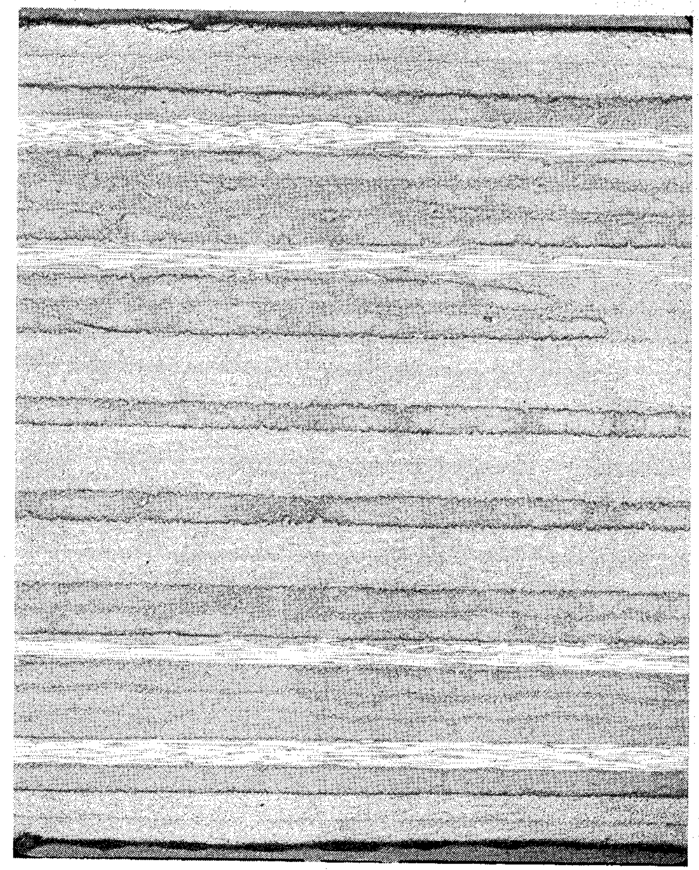


NPV4B

Figure B1. Photomicrographs (25X) of YZ Cross-Sections of the Non-Porous Laminate (see Figure 2). (Continued)

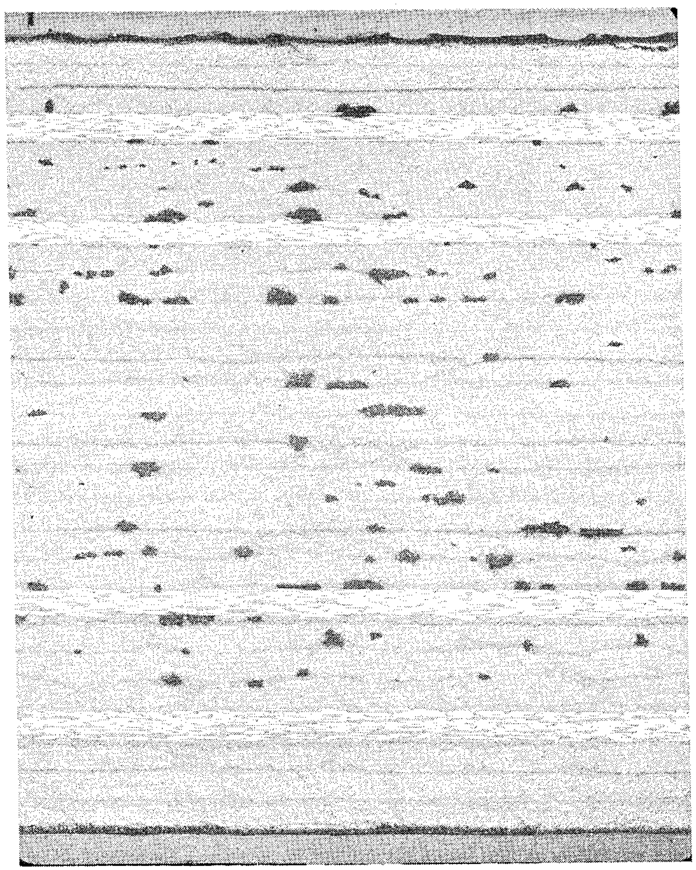


NPF2

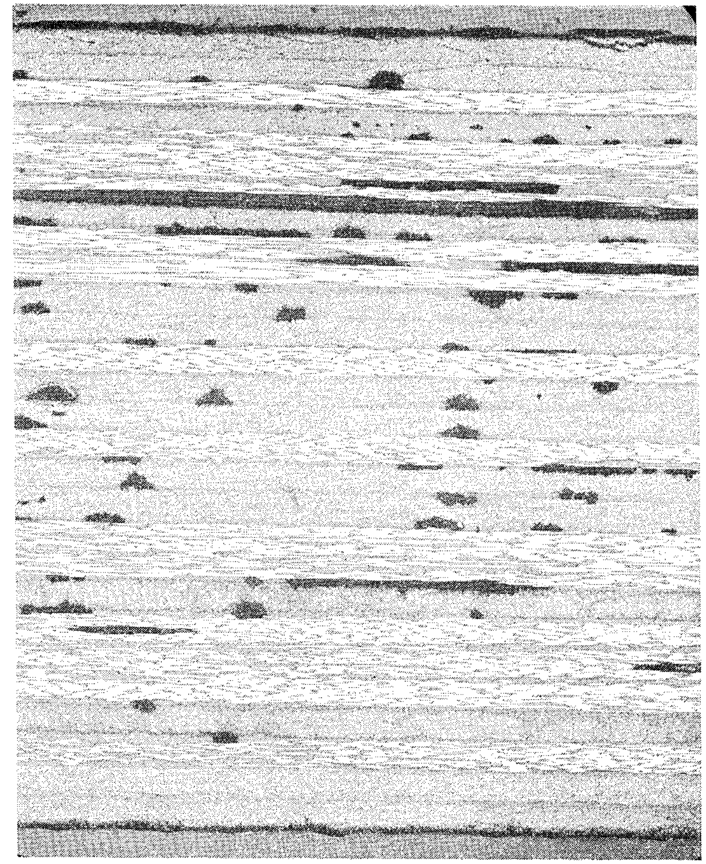


NPF3

Figure B1. Photomicrographs (25X) of YZ Cross-Sections of the Non-Porous Laminate (see Figure 2). (Concluded)

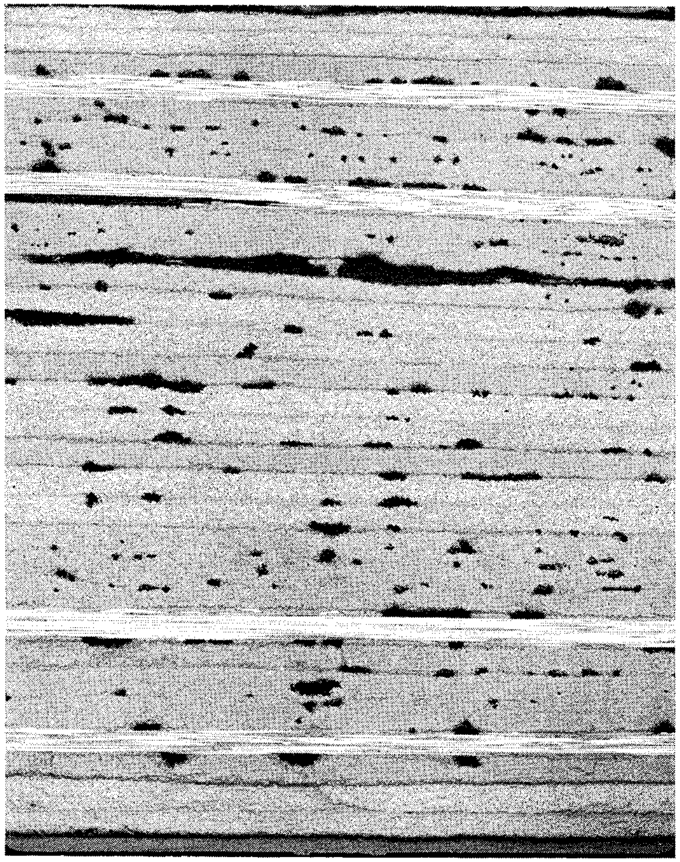


PV1B - (YZ Section)

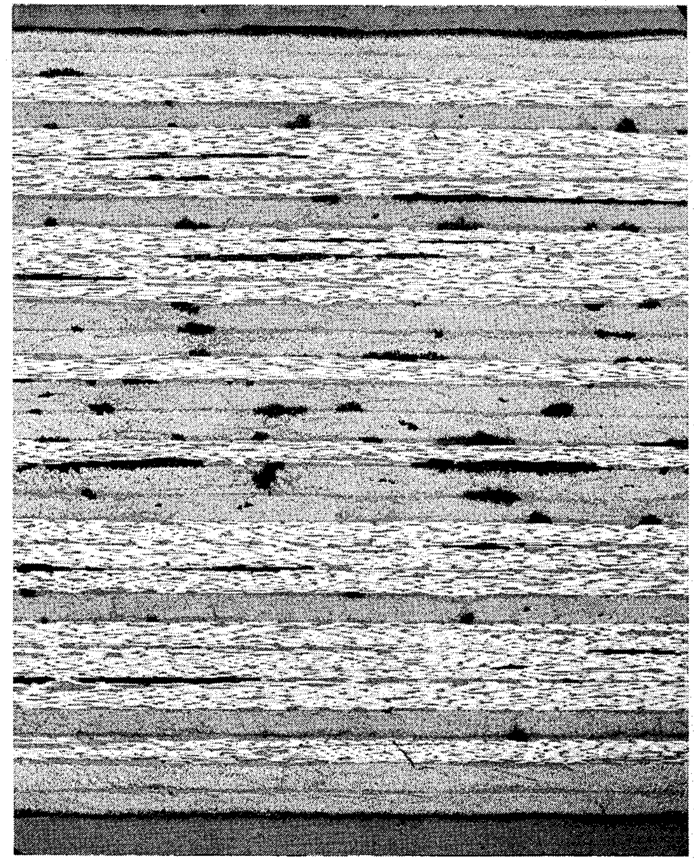


PV1B - (XZ Section)

Figure B2. Photomicrographs (25X) of XZ and YZ Cross-Sections of the Porous Laminate (See Figure 2).

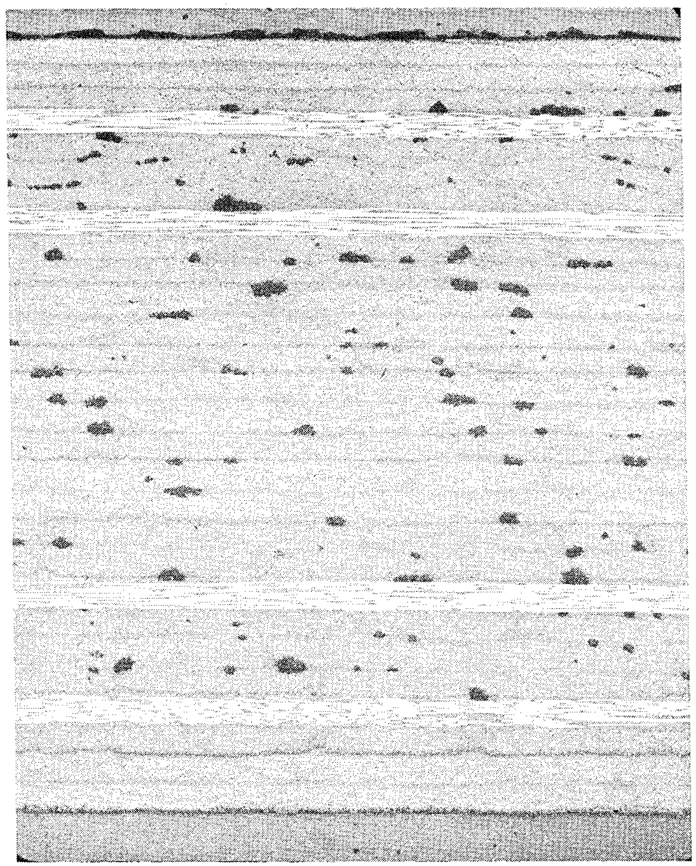


PV2B - (YZ Section)

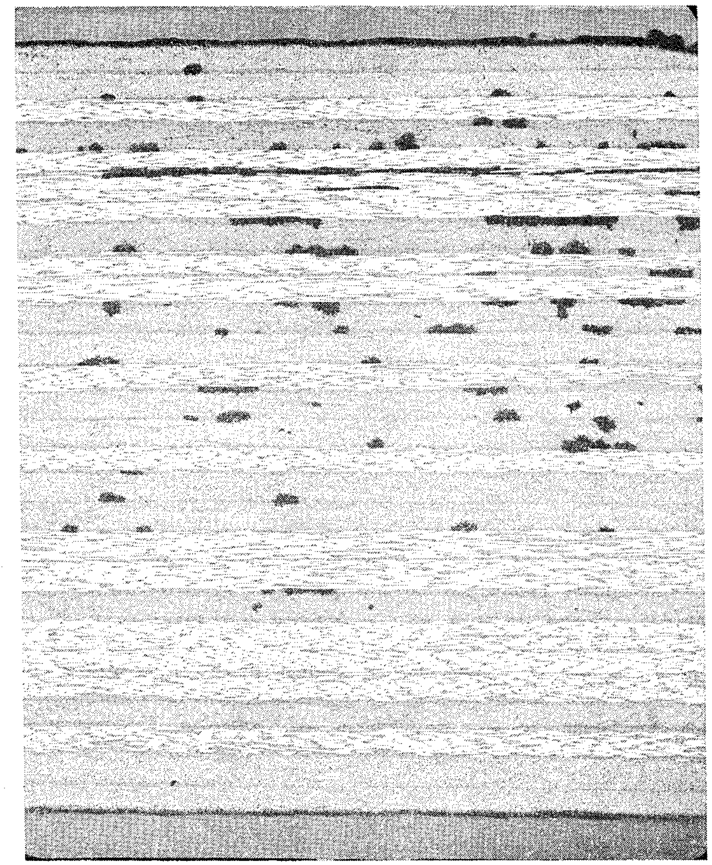


PV2B - (XZ Section)

Figure B2. Photomicrographs (25X) of XZ and YZ Cross-Sections of the Porous Laminate (see Figure 2). (Continued)

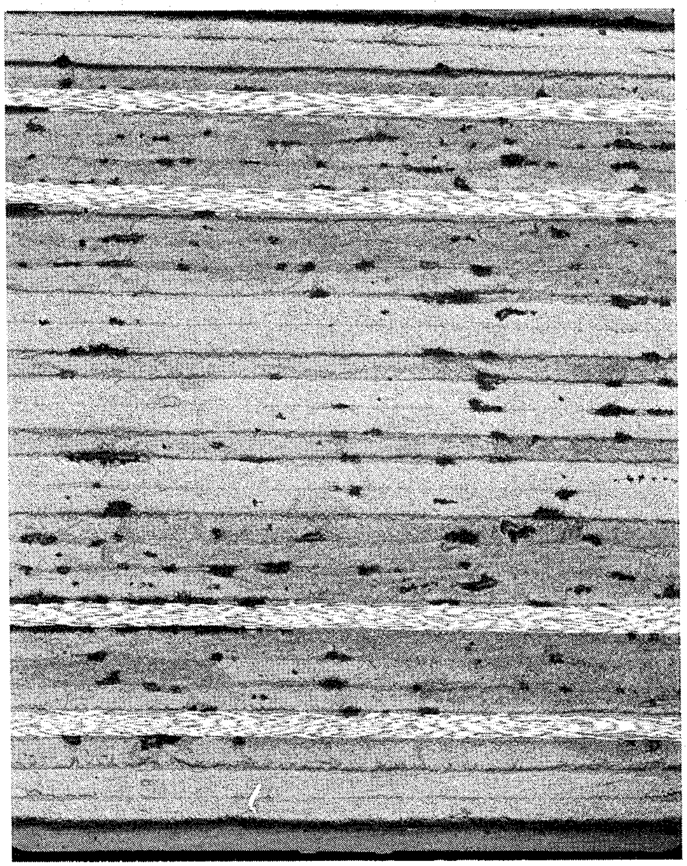


PV3B - (YZ Section)

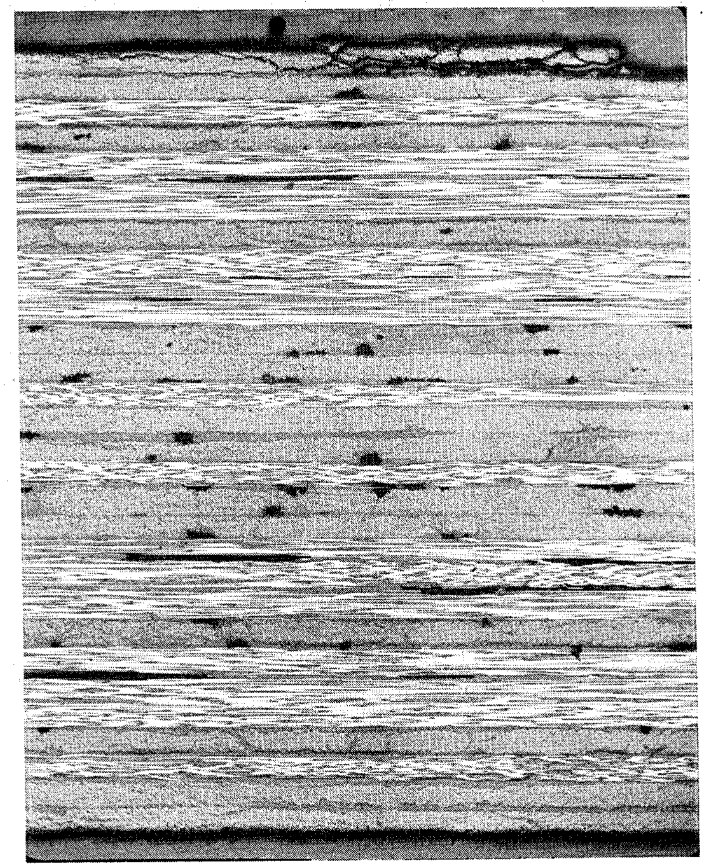


PV3B - (XZ Section)

Figure B2. Photomicrographs (25X) of XZ and YZ Cross-Sections of the Porous Laminate (see Figure 2). (Continued)

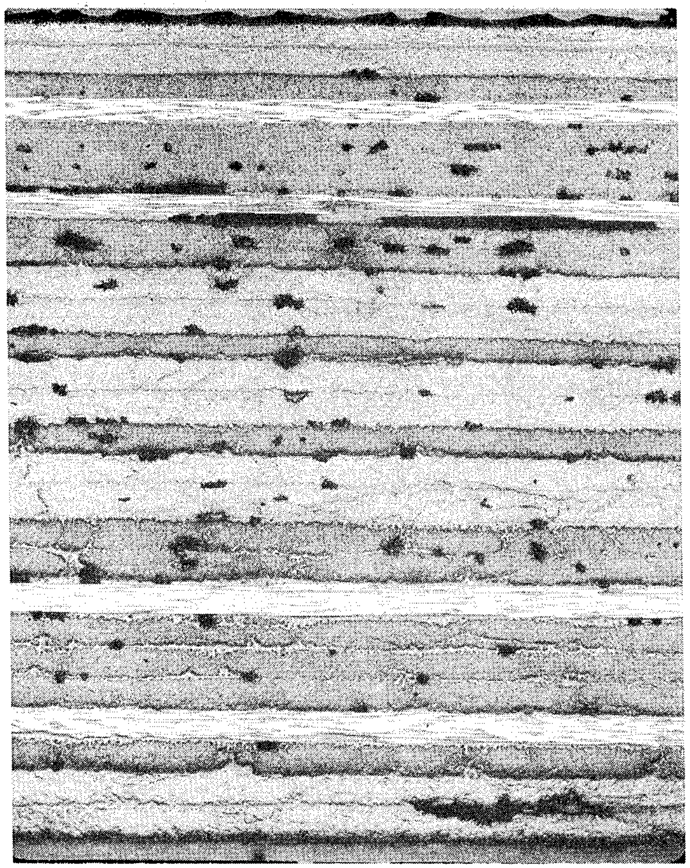


PV4B - (YZ Section)

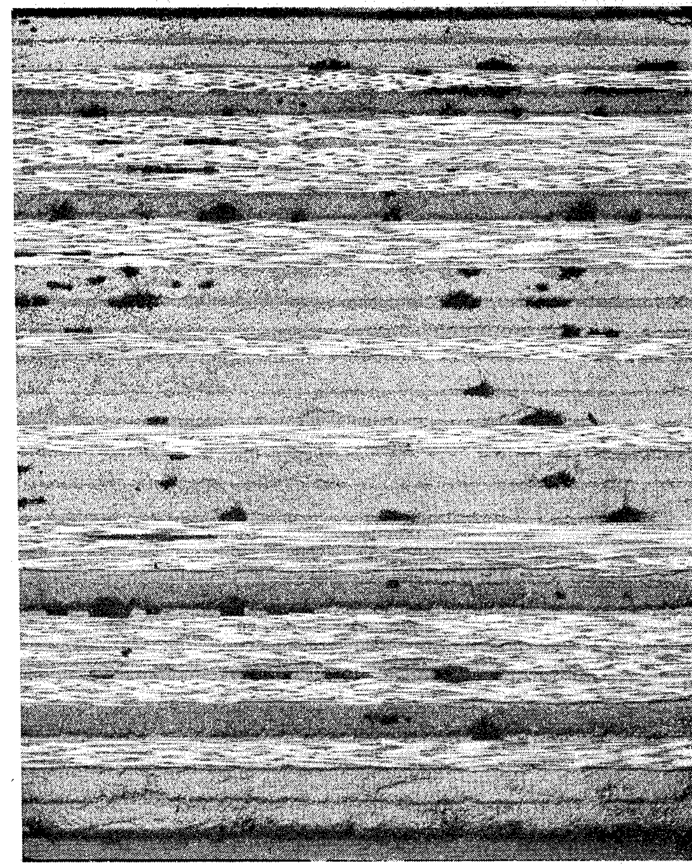


PV4B - (XZ Section)

Figure B2. Photomicrographs (25X) of XZ and YZ Cross-Sections of the Porous Laminate (see Figure 2).
(Continued)

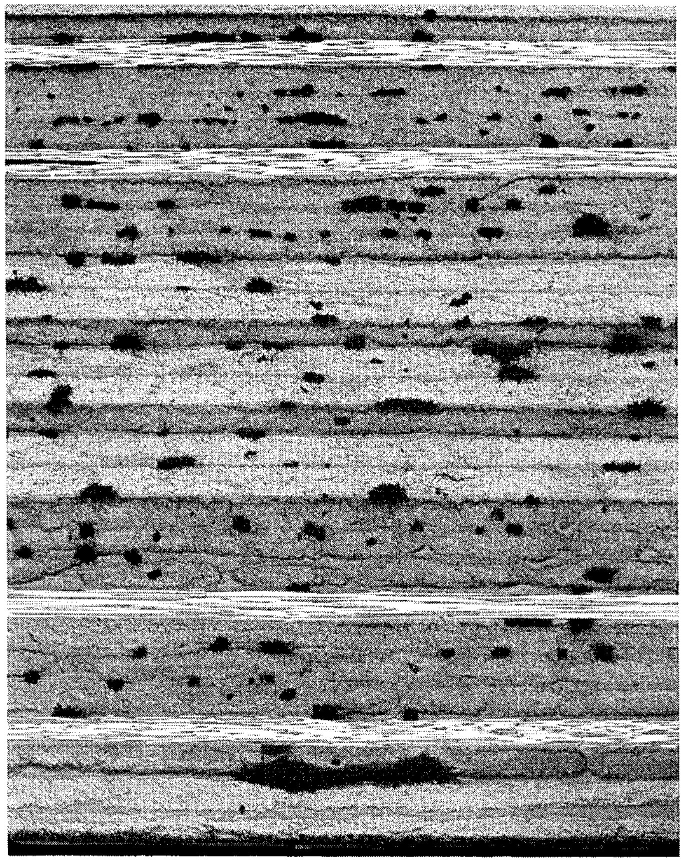


PF2 - (YZ Section)

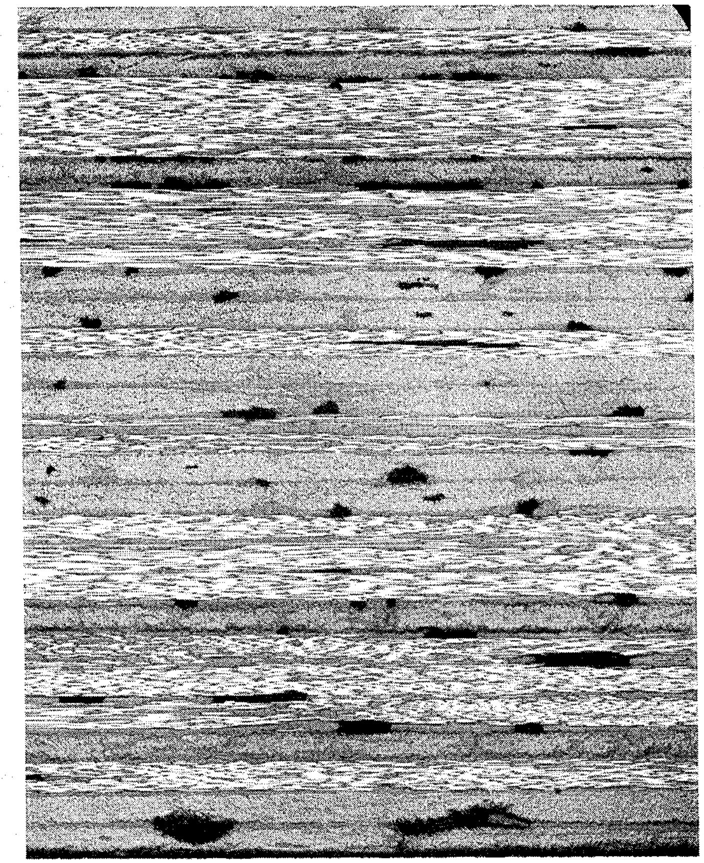


PF2 - (XZ Section)

Figure B2. Photomicrographs (25X) of XZ and YZ Cross-Sections of the Porous Laminate (see Figure 2). (Continued)



PF3 - (YZ Section)



PF3 - (XZ Section)

Figure B2. Photomicrographs (25X) of XZ and YZ Cross-Sections of the Porous Laminate (see Figure 2). (Concluded)

SAMPLE POROSITY COMPUTATION USING CHEMICAL ANALYSIS RESULTS

The following data were gathered during a chemical analysis of <u>specimen PV4</u>:

Weight of laminate = 4.35360 gm. wt.

Weight of crucible = 36.36618 gm. wt.

Weight after digestion of resin by acid = 39.40748 gm wt.

Weight of laminate & wire in water = 2.58573 gm. wt.

Weight of wire in water = 1.02383 gm. wt.

The following fiber and resin properties were assumed based on vendor quality assurance certification data for the lot number of material used in the program:

Fiber specific gravity = 1.81

Resin specific gravity = 1.29

The following computations were carried out with the above data:

Weight of laminate + crucible before resin digestion = 40.71978 gm. wt.

Weight of laminate + crucible after resin digestion = 39.40748 gm. wt.

Weight of resin = 1.31230 gm. wt.

Weight of fiber = 4.35360-1.31230 = 3.04130 gm. wt.

Resin content by weight = (1.31230/4.35360) x 100 = <u>30.14%</u>

Weight of laminate in water = 2.58573-1.02383=1.56190 gm. wt.

Buoyancy = 4.35360-1.56190 = 2.7917 gm. wt.

Specific gravity of laminate = 4.3536/2.7917 = <u>1.5595</u>

Volume of laminate = V_L = 4.35360/1.5595 = 2.79166cc

Volume of fiber = V_f = 3.0413/1.81 = 1.68028 cc

Volume of resin = V_r = 1.3123/1.29 = 1.01729 cc

Void volume (volume of porosity) = V_v

$V_L = V_f + V_V + V_v$

$2.79166 = 1.68028 + 1.01729 + V_v$

$V_v = 0.09409$ cc

Void content in laminate (by volume) = (0.09409/2.79166) X 100 = 3.37%

Resin content by volume = <u>36.44%</u>

Fiber content by volume = <u>60.19%</u>

TABLE B1. MOISTURE DATA ON NON-POROUS TRAVELERS.

SPECIMEN I.D. = 4876 SPECIMEN NO. = TEST SERIES =

NUMBER OF TRAVELERS = DATE MOISTURE CONDITIONING BEGUN =

NON-POROUS TRAVELERS

DATE	DAY	M#1	M#2	M#3	M#4	M#5	M#6	M#7	M#8	I	J	COND
12-13-82		4.891	4.841	4.859	4.883	4.592	4.572	4.550	4.554			DRY-UNTAPED
12-13-82		5.016	4.964	4.980	5.003	4.709	4.687	4.674	4.667			DRY-TAPED
1-7-83		5.033	4.980	4.995	5.018	4.725	4.703	4.691	4.683			
1-14-83		5.048	4.995	5.011	5.033	4.740	4.719	4.704	4.695	63	DAYS UNDER	
1-21-83		5.056	5.006	5.020	5.042	4.750	4.730	4.714	4.705	170°	F, 95% RH	
1-28-83		5.066	5.016	5.030	5.054	4.759	4.739	4.729	4.717	CON	DITIONS	
2-4-83		5.071	5.021	5.035	5.056	4.763	4.742	4.730	4.719			
2-11-83		5.076	5.025	5.038	5.059	4.767	4.746	4.732	4.723	IN →	1/4/83	
		1.22	1.26				1.29		1.33	OUT →	3/8/83	
2-18-83		5.081	5.035	5.048	5.068	4.776	4.758	4.741	4.731			
2-25-83		5.083	5.035	5.047	5.067	4.775	4.756	4.742	4.732			
3-4-83		5.094	5.036	5.050	5.072	4.778	4.757	4.743	4.734			
3-8-83		5.088	5.039	5.053	5.074	4.780	4.762	4.744	4.739			OUT 95% - INTO 80%
3-11-83		5.085	5.035	5.048	5.069	4.776	4.756	4.740	4.751	36	DAYS UNDER	
3-21-83		5.082	5.033	5.047	5.070	4.773	4.753	4.738	4.729	170°	F, 80% RH	
3-25-83		5.080	5.032	5.044	5.067	4.772	4.752	4.738	4.729	CON	DITIONS	
4-1-83		5.082	5.033	5.046	5.066	4.771	4.752	4.738	4.730	IN →	3/8/83	
4-8-83		5.083	5.033	5.047	5.068	4.773	4.753	4.738	4.729	OUT →	4/11/83	
4-11-83		5.080	5.030	5.044	5.066	4.770	4.759	4.735	4.728			OUT OF MOIST.
Moisture												
(% by wt.)		1.31	1.36	1.32	1.29	1.33	1.38	1.34	1.34	1.33		

TABLE B2. MOISTURE DATA ON POROUS TRAVELERS

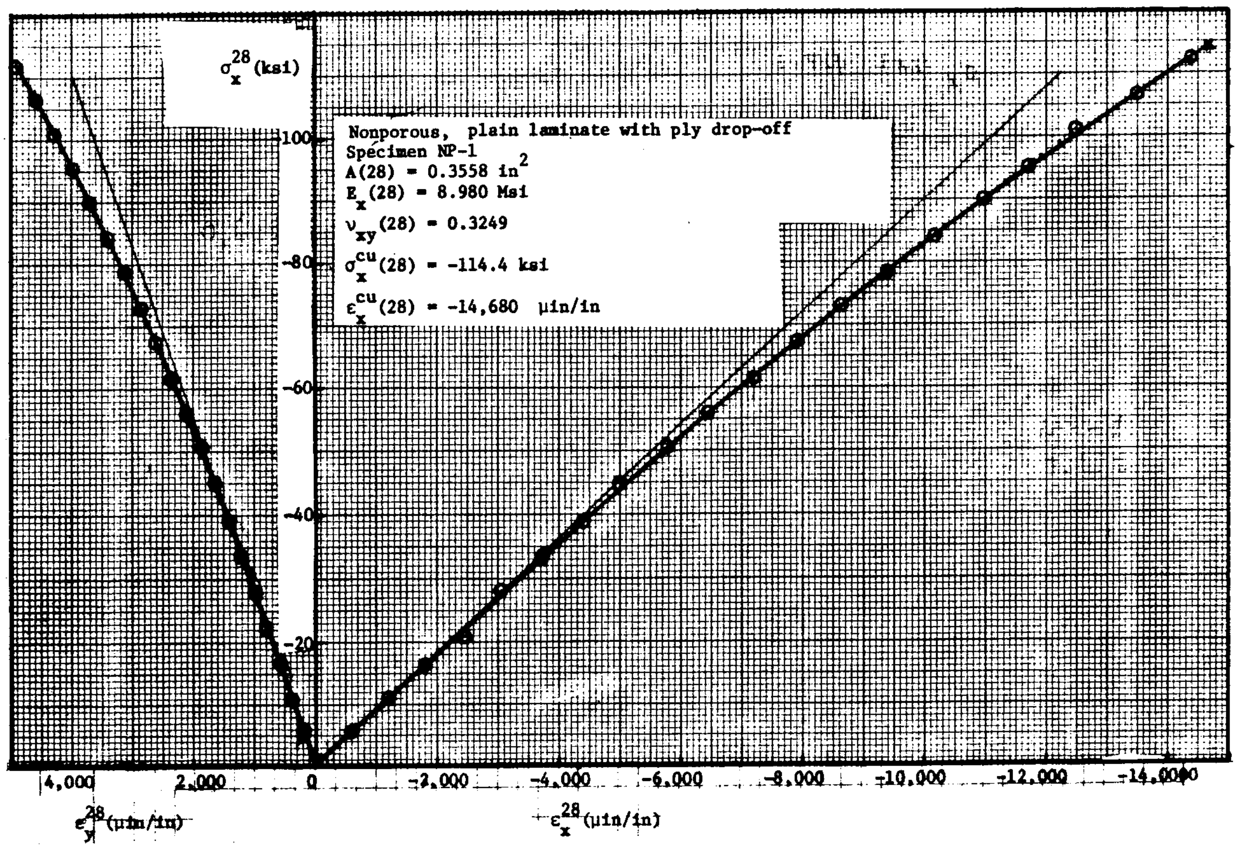
SPECIMEN I.D. =	4877	SPECIMEN NO. =		TEST SERIES =	
NUMBER OF TRAVELERS =		DATE MOISTURE CONDITIONING BEGUN =			

POROUS TRAVELERS

DATE	DAY	M#1	M#2	M#3	M#4	M#5	M#6	M#7	M#8	I	J	COND
12-13-82		4.851	4.858	4.847	4.832	4.509	4.505	4.486	4.492			DRY-UNTAPED
12-13-82		4.974	4.989	4.974	4.960	4.628	4.626	4.602	4.614			DRY-TAPED
1-7-83		4.992	5.018	4.993	4.979	4.647	4.647	4.621	4.635			
1-14-83		5.009	5.024	5.009	4.994	4.663	4.661	4.636	4.649	63	DAYS UNDER	
1-21-83		5.019	5.035	5.017	5.004	4.672	4.672	4.647	4.659	170°F	and 95%	
1-28-83		5.029	5.047	5.030	5.016	4.685	4.686	4.650	4.674	RH	CONDITIONS	
2-4-83		5.031	5.048	5.033	5.017	4.687	4.686	4.660	4.674			
2-11-83		5.034	5.051	5.035	5.020	4.689	4.689	4.663	4.675	IN→1/4/83		
										OUT→3/8/83		
2-18-83		5.041	5.061	5.044	5.028	4.694	4.694	4.668	4.681			
2-25-83		5.045	5.060	5.044	5.029	4.695	4.696	4.670	4.681			
3-4-83		5.046	5.061	5.047	5.032	4.697	4.697	4.671	4.682			
3-8-83		5.051	5.065	5.049	5.032	4.699	4.699	4.672	4.683			OUT 95% INTO 80%
3-11-83		5.044	[illegible]	5.044	5.027	4.694	4.693	4.669	4.680			
3-21-83		5.046	5.061	5.045	5.030	4.695	4.695	4.670	4.679			
3-25-83		5.042	5.055	5.041	5.026	4.690	4.690	4.665	4.674	36 DAYS	UNDER	
4-1-83		5.038	5.053	5.039	5.022	4.688	4.688	4.661	4.673	170°F,	80% RH	
4-8-83		5.040	5.054	5.040	5.024	4.690	4.689	4.665	4.676	COND	ITIONS	
4-11-83		5.037	5.051	5.036	5.021	4.687	4.686	4.661	4.672	IN→3/8/83		OUT OF MOIST
										OUT→4/11/83		
M(% by wt.)		1.30	1.28	1.28	1.26	1.31	1.33	1.32	1.29	(1.30)		

APPENDIX C

STRESS-STRAIN CURVES FROM STATIC COMPRESSION TESTS



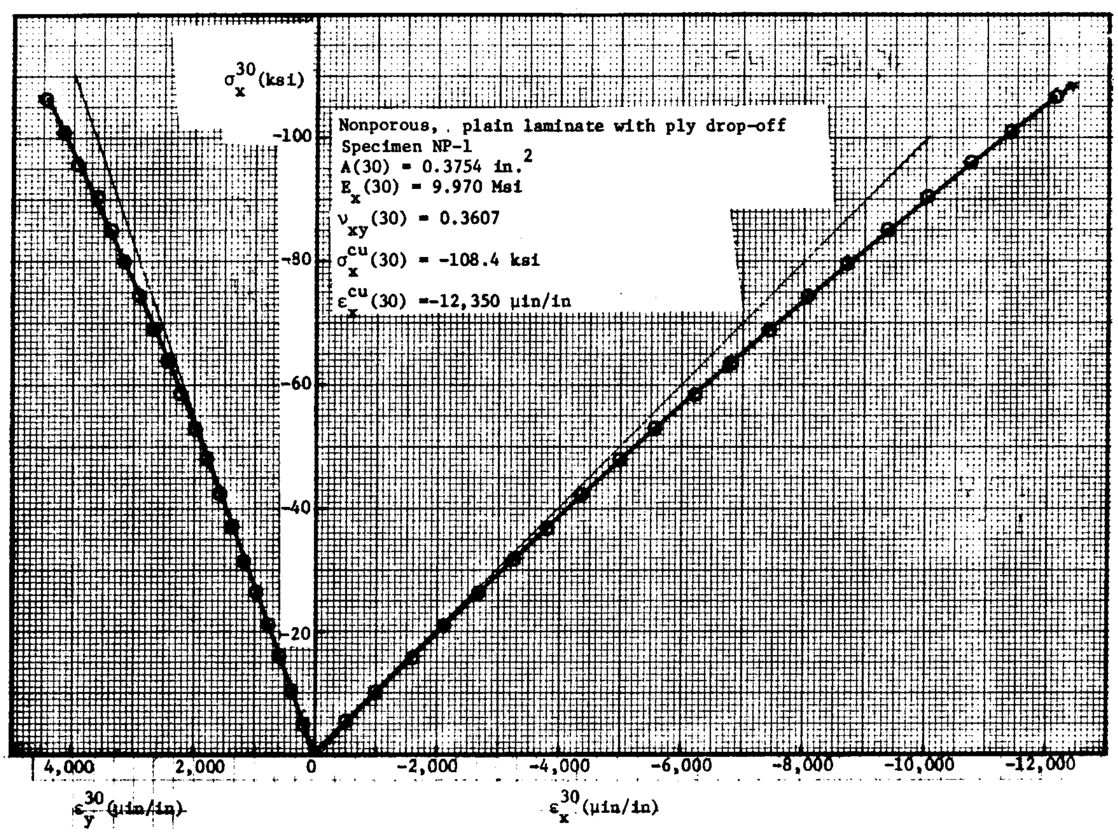


Figure C1. Stress-Strain Curves for the 28- and 30-ply Sections of Specimen NP-1.

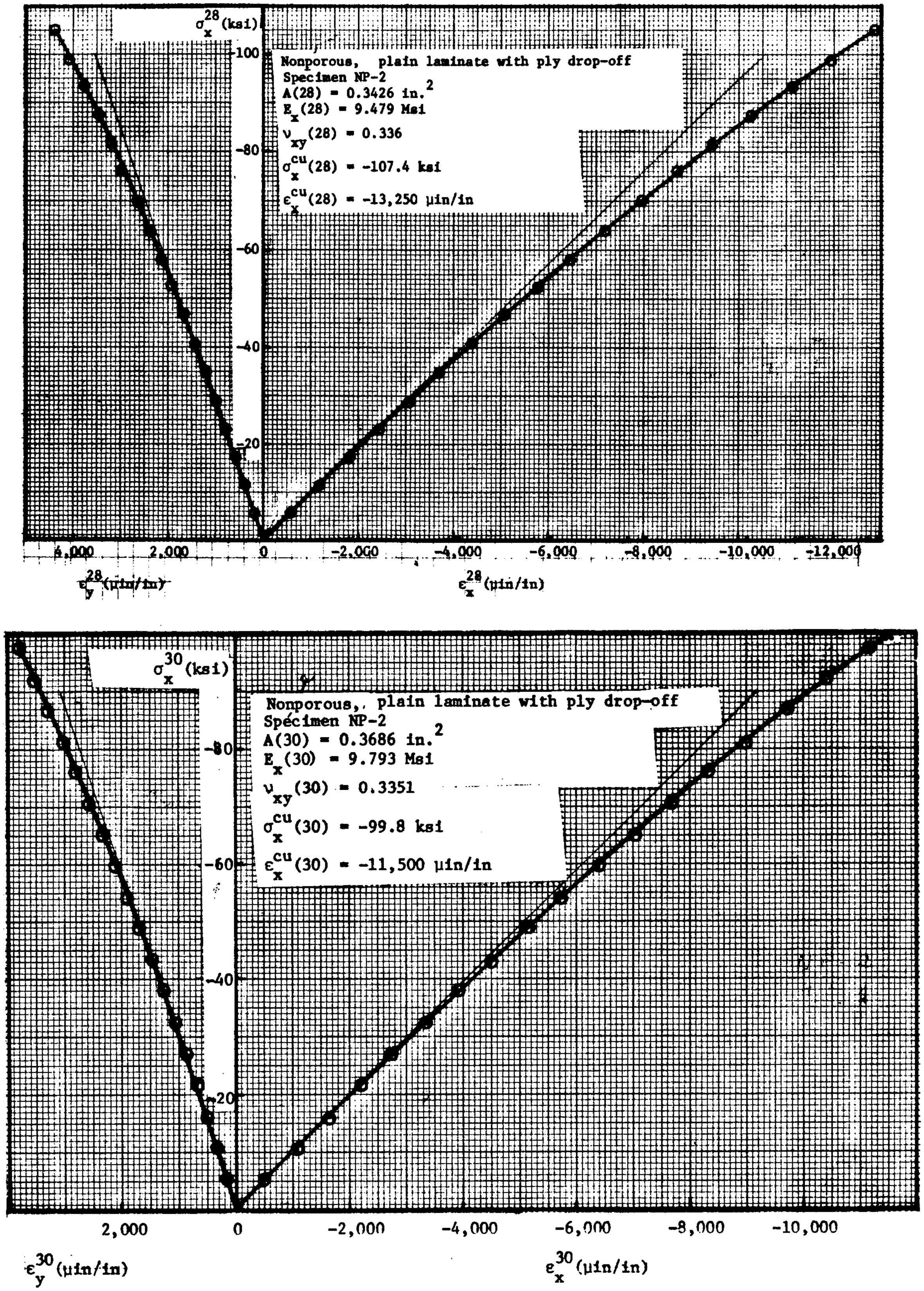
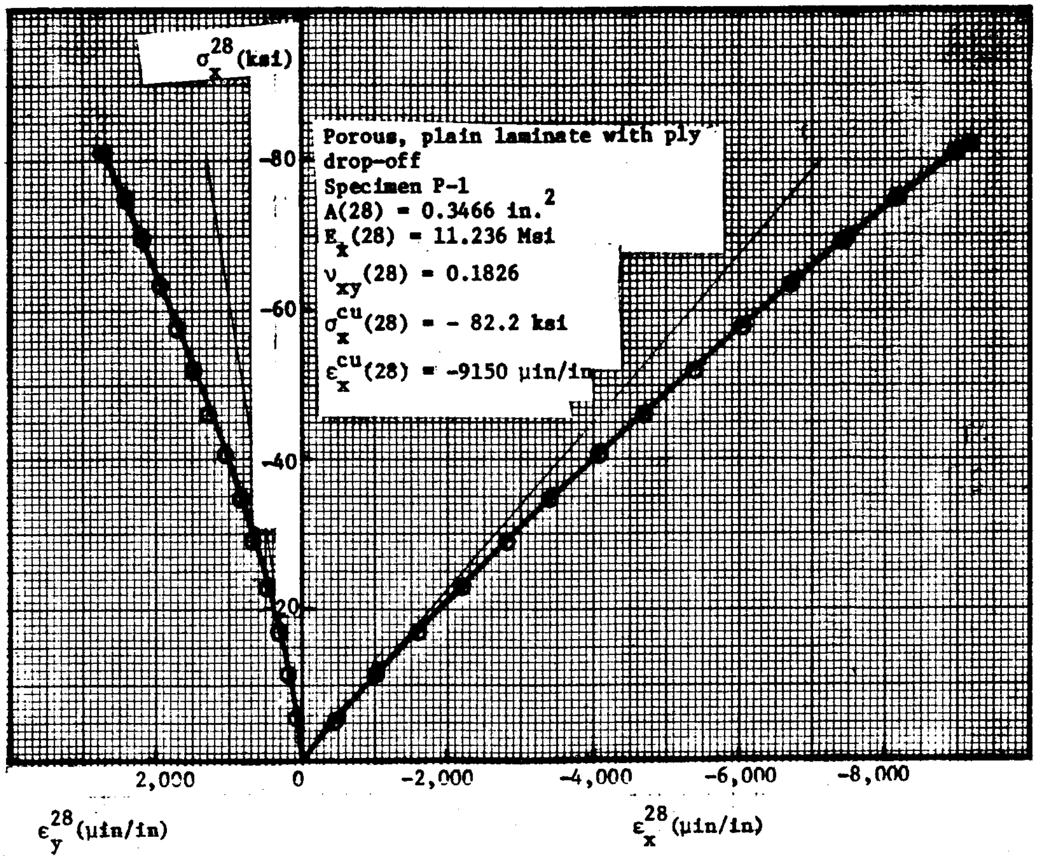


Figure C2. Stress-Strain Curves for the 28- and 30-ply Sections of Specimen NP-2.



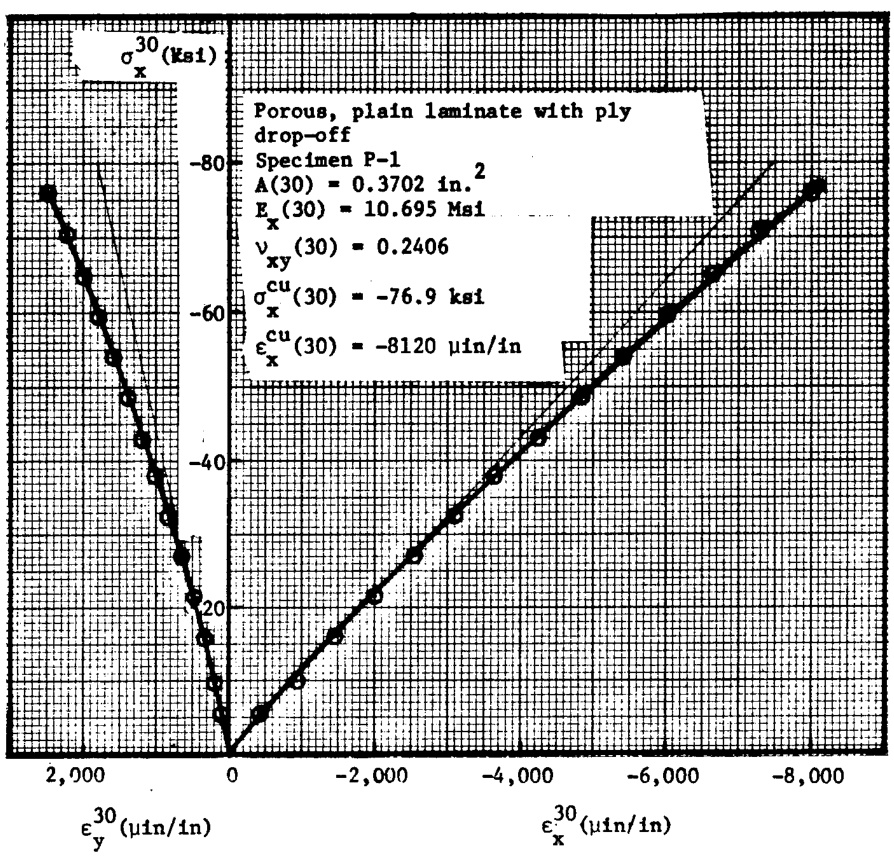


Figure C3. Stress-Strain Curves for the 28- and 30-ply Sections of Specimen P-1.

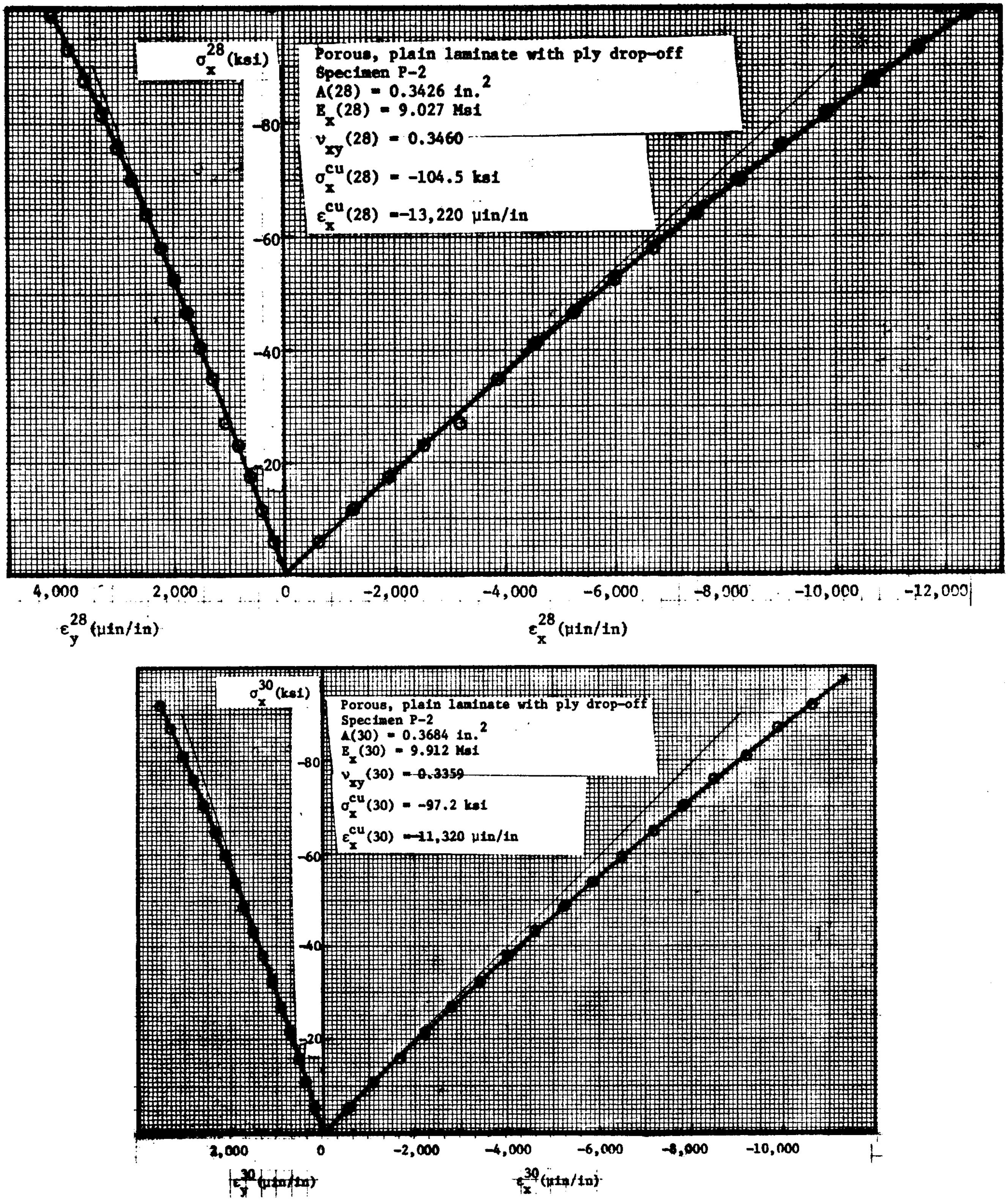


Figure C4. Stress-Strain Curves for the 28- and 30-ply Sections of Specimen P-2.

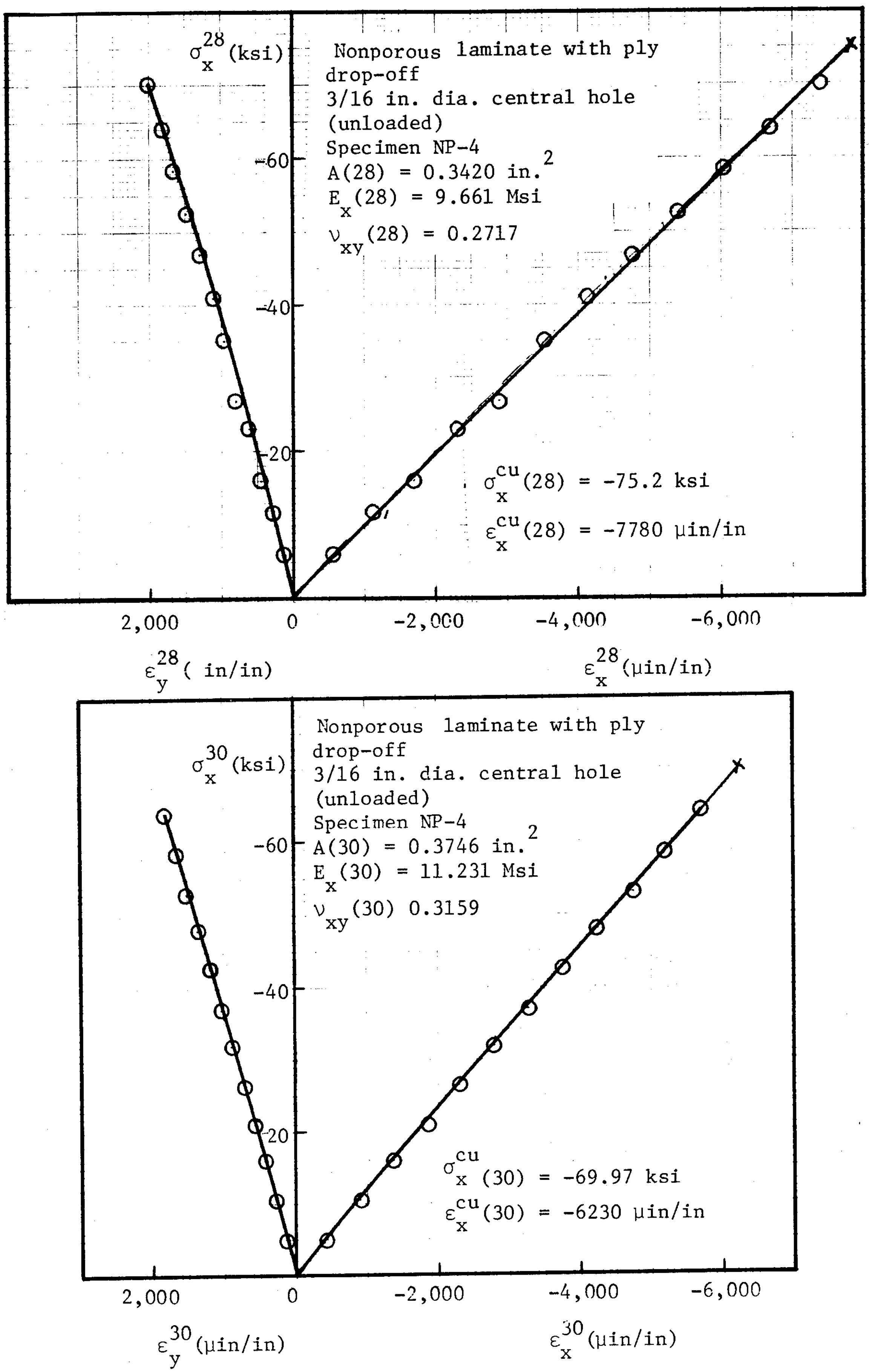


Figure C5. Stress-Strain Curves for the 28- and 30-ply Sections of Specimen NP-4.

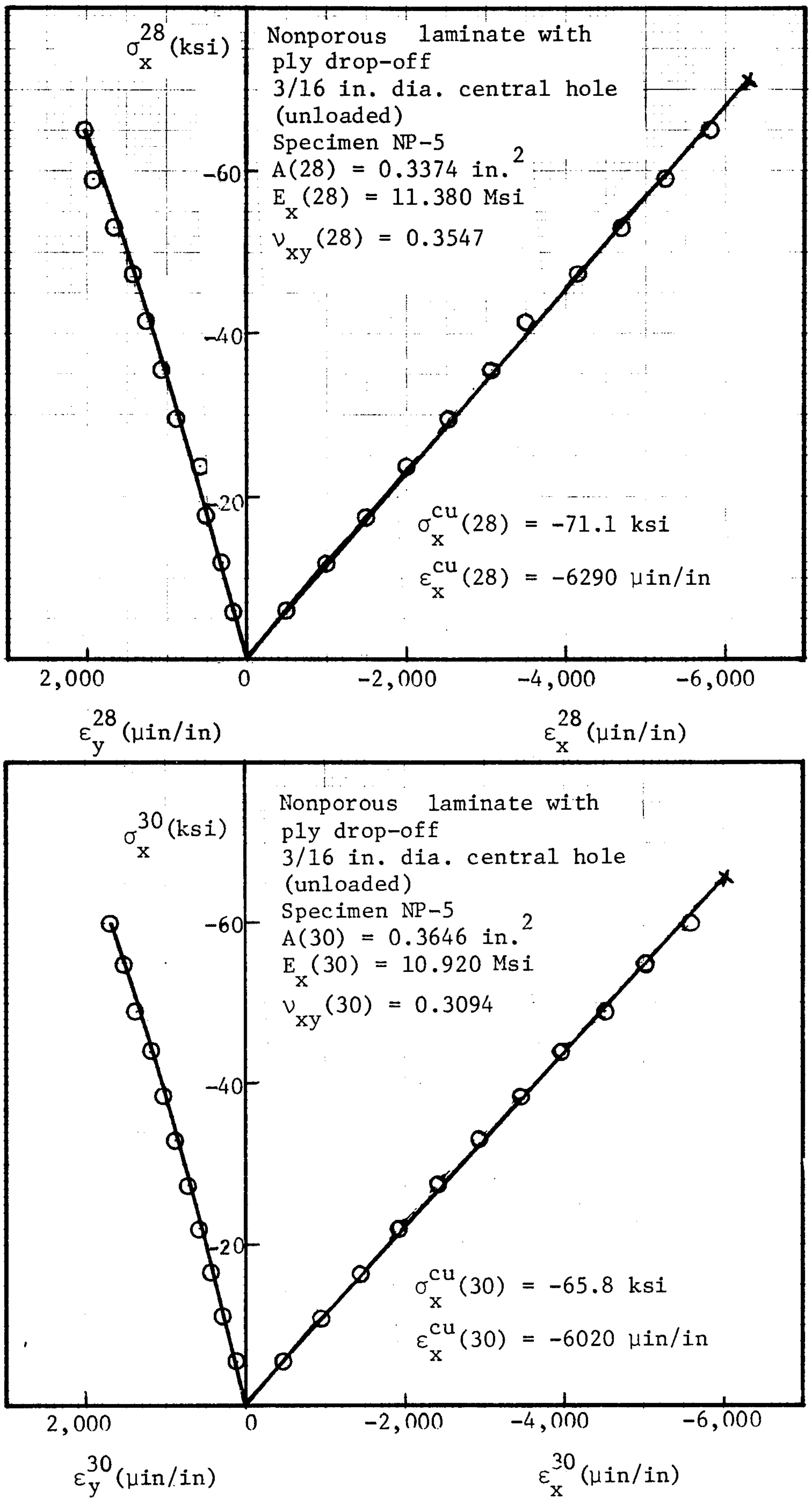
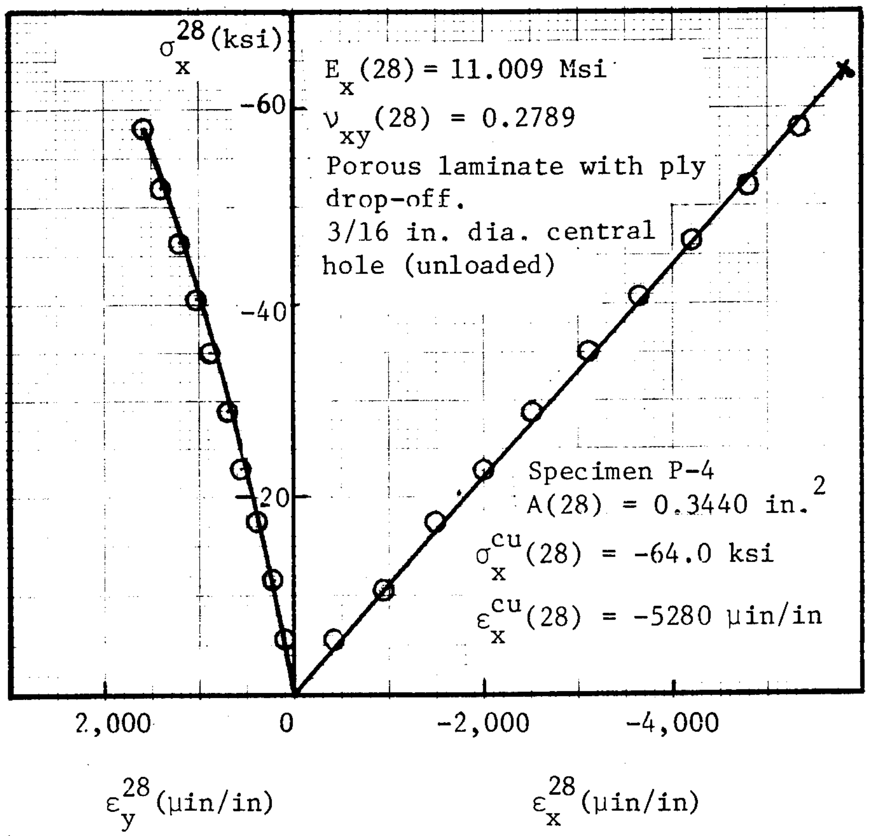


Figure C6. Stress-Strain Curves for the 28- and 30-ply Sections of Specimen NP-5.



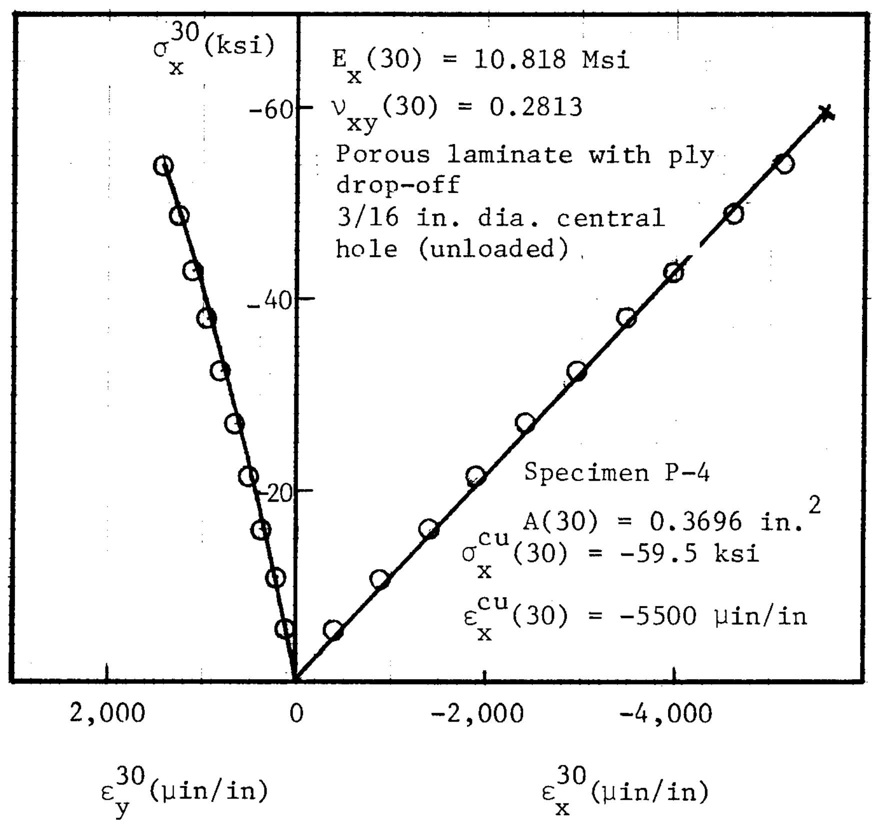
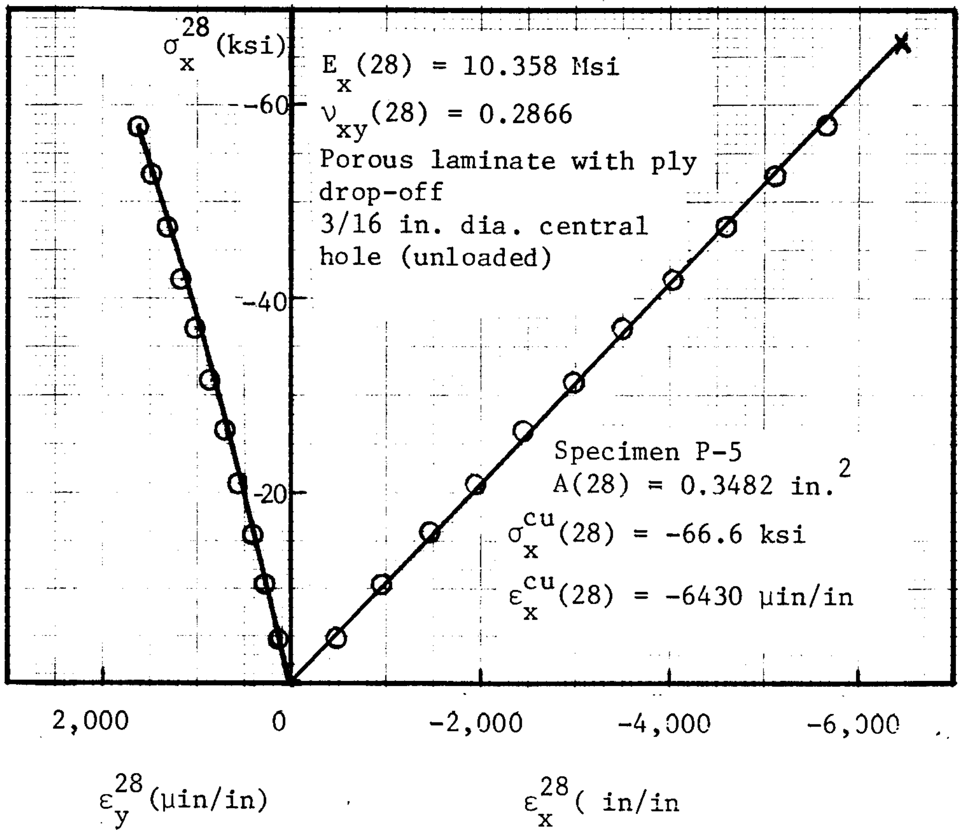


Figure C7. Stress-Strain Curves for the 28- and 30-ply Sections of Specimen P-4.



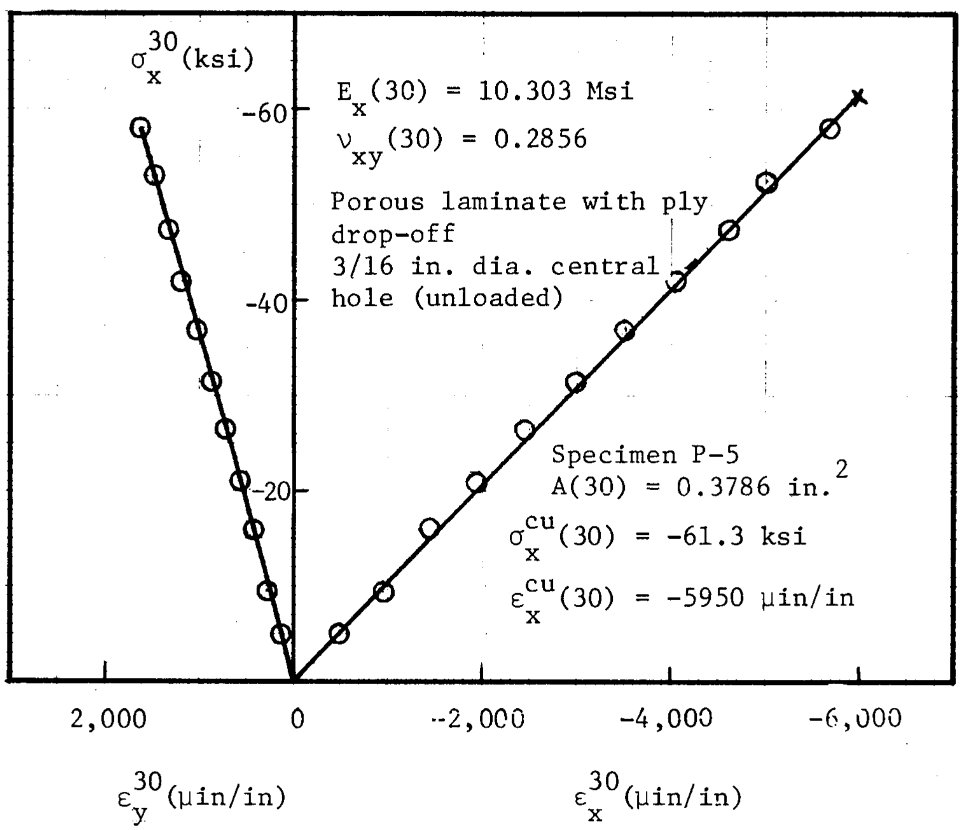
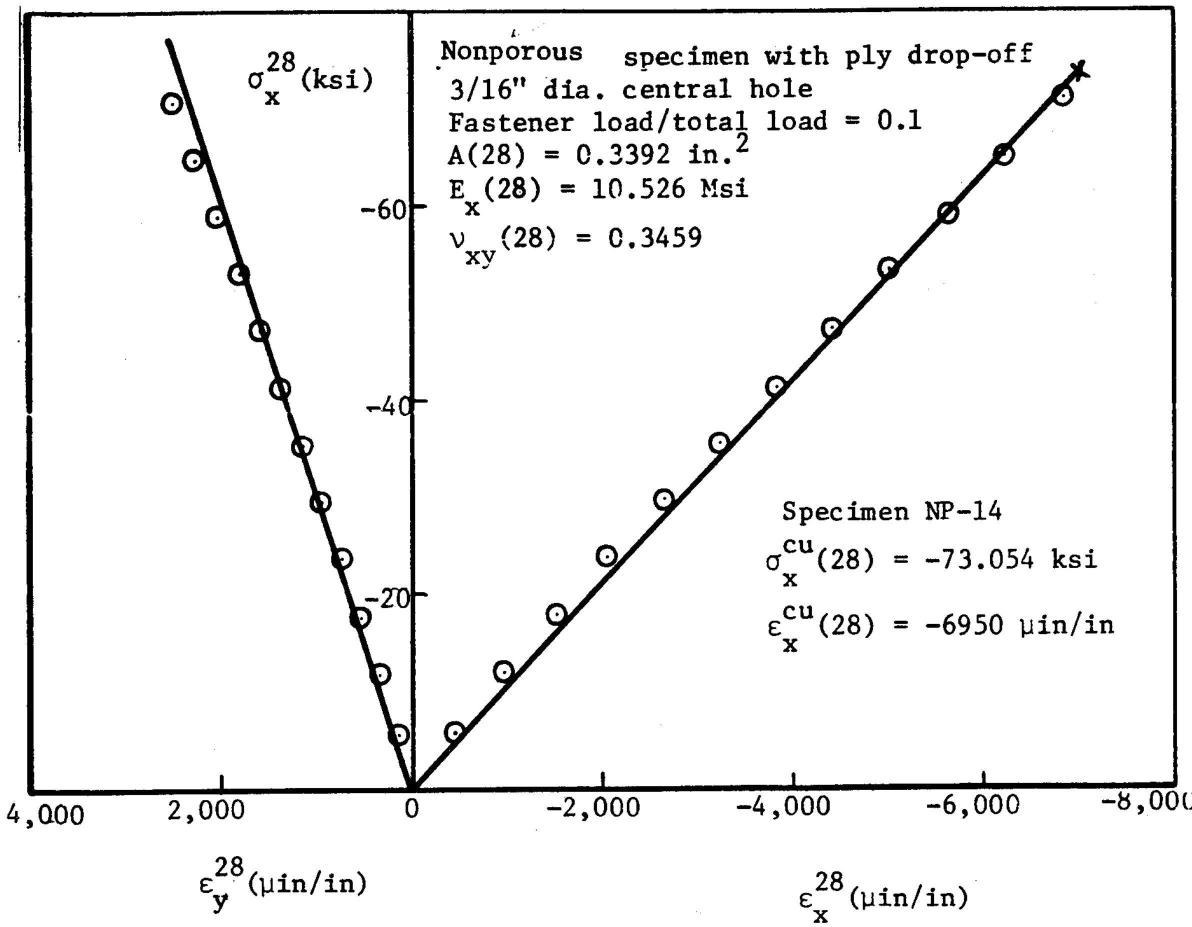


Figure C8. Stress-Strain Curves for the 28- and 30-ply Sections of Specimem P-5.



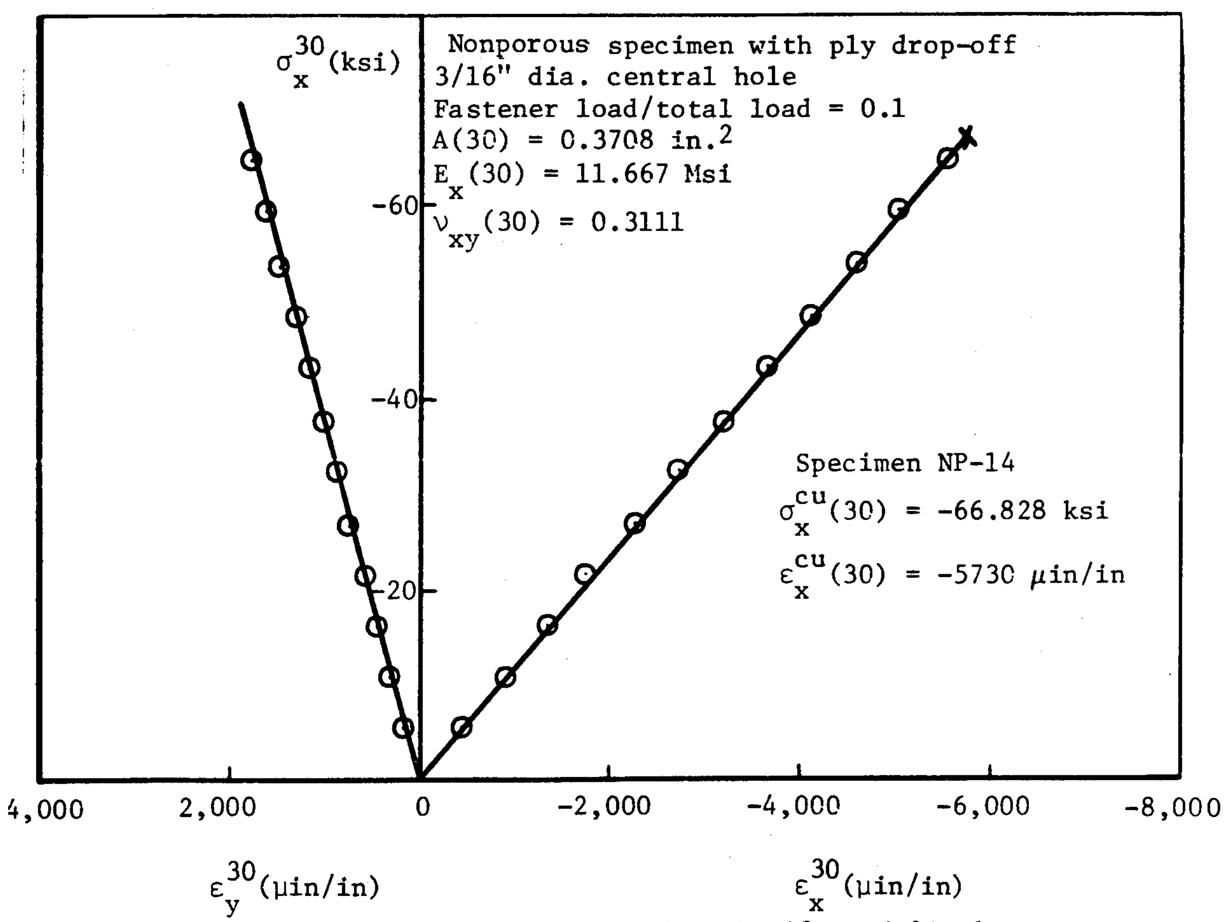
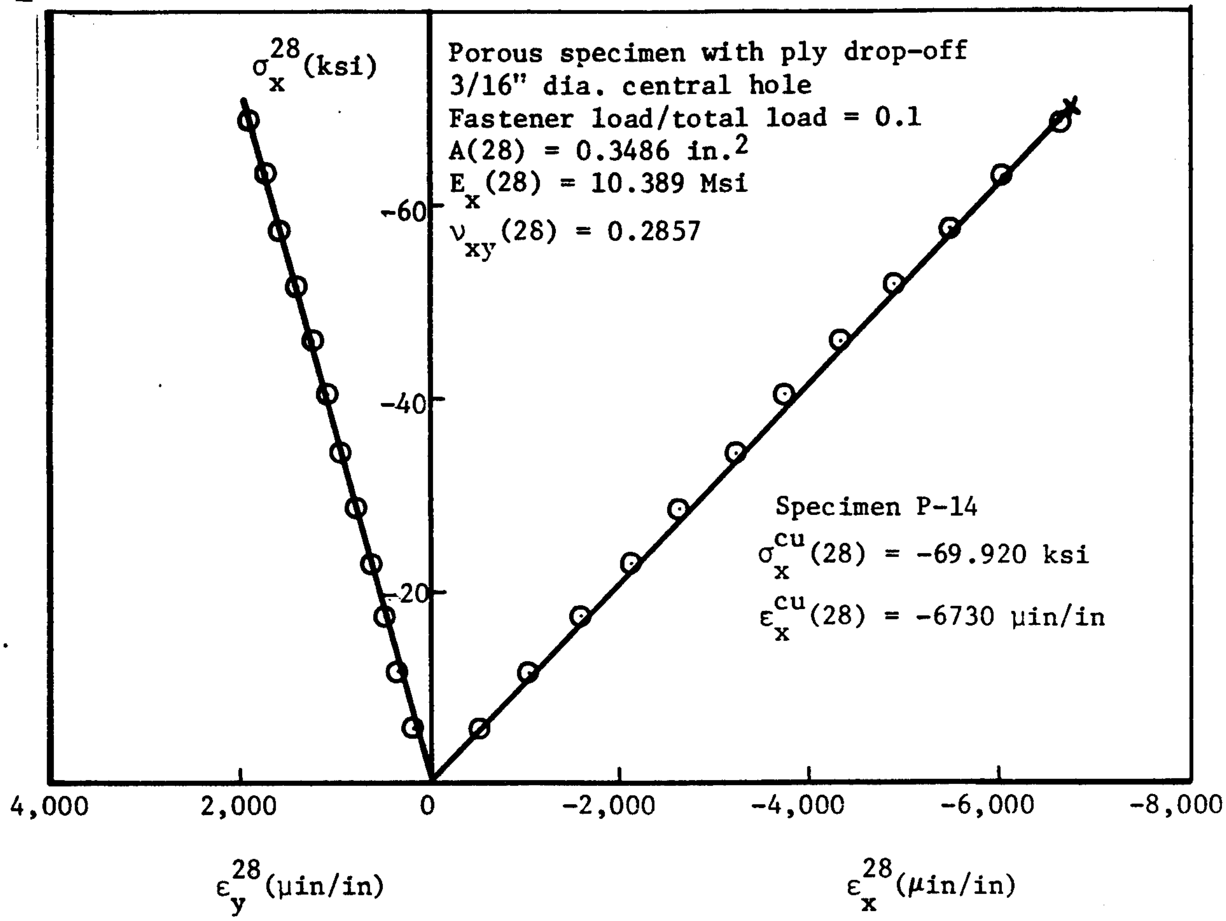


Figure C-9. Stress-Strain Curves for the 28- and 30-ply Sections of Specimen NP-14.



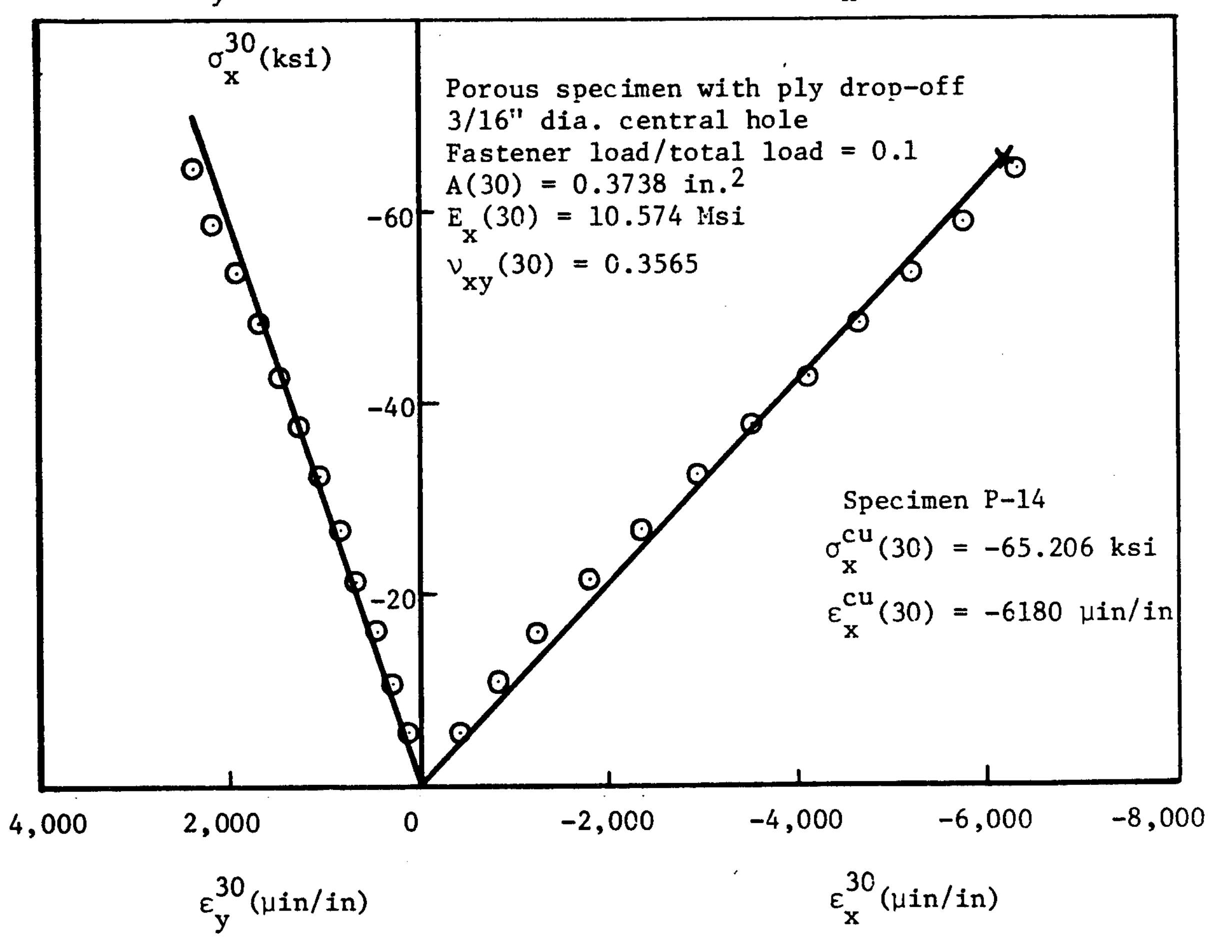


Figure C10. Stress-Strain Curves for the 28- and 30-ply Sections of Specimen P-14.

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